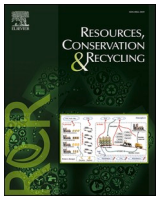
Resources, Conservation & Recycling 222 (2025) 108436



Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling



Full length article



Enhancing supply resilience for critical materials: case study of gallium supply in the United States

Jannis Wesselkaemper [a,1], Alex C. Newkirk [b,c,1], Thomas P. Hendrickson [a], Nadiyah Helal [a], Prakash Rao [c], Sarah J. Smith [a,*], Andrew Z. Haddad [d,*]

[a] Energy Analysis and Environmental Impacts Division, Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[b] Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA
[c] Building Technologies and Urban Systems, Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[d] Energy Storage and Distributed Resources Division, Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

ARTICLE INFO

Keywords:
Gallium
Supply chain
Critical minerals
Recycling
Material flow analysis
Cost analysis

ABSTRACT

Accelerating energy technology development will increase demand for critical raw materials, such as gallium, that enable clean energy technologies. Processing of gallium is concentrated in mainland China (98 % of global production in 2023), resulting in high supply risks for importing countries. To investigate pathways for more resilient supply, we develop a material flow analysis and apply it to the United States, showing the impacts of future domestic primary raw material production and end-of-life (EoL) product recycling on reducing import reliance of raw gallium metal. We complement this analysis with a techno-economic assessment of North American gallium production costs under various demand growth scenarios. Our results indicate that sufficient domestic feedstocks exist to meet U.S. demand under most scenarios by 2035, while EoL recycling can supply up to 50 % under a low-demand growth scenario. Domestic primary production shows significant cost advantages over gallium recycling.

1. Introduction

The adoption of new energy technologies is increasing (IEA, 2024). These technologies demand high volumes of specific materials, such as lithium, cobalt, nickel, graphite, and gallium (IEA, 2024), that often have limited feedstocks with geographically concentrated supply chains (Cheng et al., 2024; United States Geological Survey, 2024; Baars et al., 2021; Sun et al., 2024; Wesselkämper et al., 2024; Haddad et al., 2023). This results in high risks of supply disruption due to import reliance and limited supply chain infrastructure. These vulnerabilities are ushering in a new era where energy relevant elements, such as gallium, are increasingly being classified as “critical” by both the European Union (European Commission, 2024) and the U.S. Department of Energy (Bauer et al., 2023). The classification indicates a shift towards onshoring critical materials supply chains as an essential step towards energy independence. For example, the EU Critical Raw Materials Act sets minimum domestic mining, processing and recycling limits for critical material supply by 2030 to improve supply chain resilience and increase circularity. Furthermore, no >65 % of critical material demand is allowed to be sourced from a single external country by 2030 (European Commission, 2024). As a result, the regional industry explores opportunities to produce gallium, such as the Greek leading alumina producer Metlen. Recently, Metlen announced investing around 300 million EUR to develop gallium production of around 50 t annually, which could fully cover the EU’s future gallium demand, based on Metlen’s alumina operations (Bauer et al., 2023).

Gallium differs from many other energy-critical elements in that it does not occur in concentrated ore deposits in Earth’s crust. Instead, gallium is found only in trace amounts, primarily in bauxite (an aluminum-bearing ore) and sphalerite (a zinc-bearing ore), and is recovered as a byproduct from the waste streams and residues generated during the refining of these primary metals. The largest resource of primary gallium is bauxite, which yields a gallium content of around 57 ppm (regionally even up to 75 ppm) (United States Geological Survey, 2024; IEA 2024). Globally, approximately 90–96 % of consumed gallium is produced during the production of alumina from mined bauxite via the well-established Bayer process (Song et al., 2022; Gao et al., 2024; Frenzel et al., 2016; Lu et al., 2017), while only 21 % of the total gallium

* Corresponding authors.
E-mail addresses: sjsmith@lbl.gov (S.J. Smith), azhaddad@lbl.gov (A.Z. Haddad).
[1] J.W and A.C.N. contributed equally

https://doi.org/10.1016/j.resconrec.2025.108436
Received 22 January 2025; Received in revised form 23 May 2025; Accepted 30 May 2025
Available online 7 June 2025
0921-3449/Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

contained in bauxite is extracted successfully (Gao et al., 2024). The remaining 4–10 % of primary gallium is extracted from sphalerite zinc ores with 50 ppm gallium content in the United States (Lu et al., 2017). After smelting and refining of the mined zinc ore, gallium remains in the zinc leachate residue (ZLR) as waste, from which both zinc and gallium are extracted in further refining cycles (Gao et al., 2024). Both primary refinement processes are active in North America. In 2023, zinc was mined at seven different U.S. mines while alumina was refined by solely one company in a facility in Louisiana, which is supplied with bauxite from Jamaica. In addition, three different companies at sites in Alabama, Arkansas, and Georgia produced small amounts of bauxite, which are used in non-metallurgical applications (United States Geological Survey, 2024).

The global demand for gallium has been increasing rapidly while reserves in bauxite and zinc continue to deplete. From 2000 to 2021, around 15 % of global gallium reserves were consumed during mining processes (over 300 kt), while only 2 % of contained gallium (5.5 kt) was extracted due to inefficient mining and refining processes and lack of market drivers to extract more (Han et al., 2024). In the same period, global demand increased by 330 % from 101 t in 2000 to 432 t in 2021 (Han et al., 2024) and is expected to further grow to 3000 t in 2050 (Song et al., 2022). Gallium, mainly in the form of gallium arsenide (GaAs) and gallium nitride (GaN), is an essential semiconductor material to produce low-energy consuming and high-computation speed chips (or integrated circuits (ICs)), energy-efficient light-emitting diodes (LEDs), copper-indium-gallium-selenide (CIGS)-type solar cells. Additionally, small amounts of gallium are often added as a doping agent to neodymium-iron-boron (NdFeB) permanent magnets, commonly used in electric vehicles and wind turbines (Løvik et al., 2015; Lu et al., 2017; Huang et al., 2022), to enhance magnetic properties and performance.

In Fig. 1, country concentrations of upstream gallium supply chains are shown. In 2023, with 600 t of primary production, China accounted for around 98 % of global gallium supply (United States Geological Survey, 2024). Meanwhile, the United States has been importing 100 % of the domestically consumed gallium over the past decades (United States Geological Survey, 2024). Such concentrated supply chains are vulnerable to disruptions (e.g., geopolitical, regulatory, labor, natural hazard) that may impact regional economies and global value chains. In 2023, China leveraged supply chain control by imposing export restrictions on several materials, including germanium and gallium compounds, which affected importing economies, such as the United States (Bauer et al., 2023). In late 2024, China further strengthened enforcement of these regulations by implementing export bans (Lv and Munroe, 2024). This demonstrates the risk critical material supply poses to the energy transition in import-reliant countries, including the United States and other countries that are highly reliant on gallium production to meet clean energy and energy resilience goals. To decrease import-dependency on critical materials and improve supply chain resilience, many countries are exploring alternative supply, both domestic production of primary raw materials and secondary supply by domestic recycling of production scrap and end-of-life (EoL) products (Eggert et al., 2016). In this research, using gallium in the United States as a case study, we evaluate potential supply pathways through integrated material flow and techno-economic analyses.

Recent scholarship investigated gallium flows through global supply networks. Material flow analyses (MFAs) detailed the entire gallium life cycle (i.e., from raw materials extraction to final disposal) to highlight vulnerabilities, and provide recommendations for enhancing resilience. Prior research investigated global gallium flows from 2000 to 2020 and 2021, respectively, showing the increasing supply chain concentration in China, and finding that current practices of gallium extraction, compound fabrication, and product manufacturing are highly inefficient (Han et al., 2024; Gao et al., 2024). These studies concluded that concerted recycling activities could leverage EoL gallium for more sustainable and resilient supply. An MFA study of gallium flows in 2011 indicated inefficient use of gallium in production waste and suggested

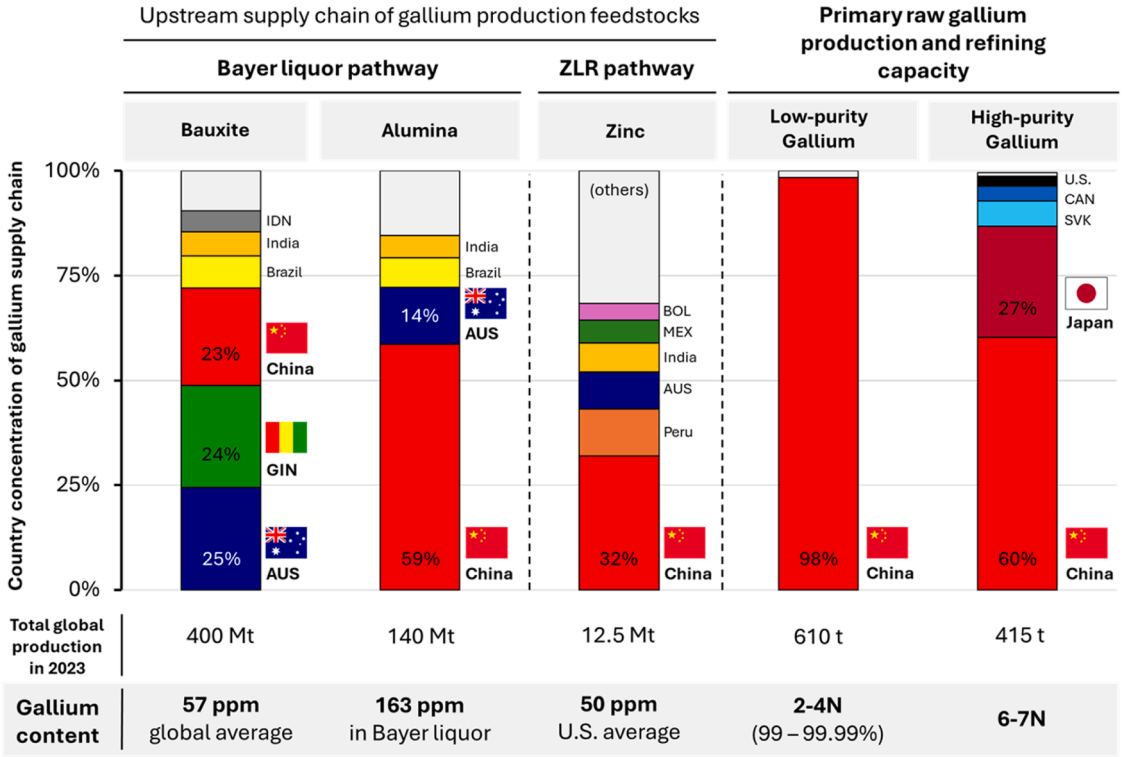


Fig. 1. Country concentration, total global production in 2023, and gallium contents in upstream gallium supply chain stages. Gallium is produced as a by-product by two pathways (refinement of Bayer liquor waste and zinc leaching residue (ZLR)), before being refined from low-purity to high-purity gallium for further compound fabrication and use in end-applications. Note: 6–7 N refers to 99.9999–99.99999 % gallium content (high-purity gallium). Sources: (United States Geological Survey 2024; Løvik et al., 2015; Lu et al., 2017; Nassar et al., 2024).

EoL recycling[112]. Finally, previous research studies derived that global gallium supply from bauxite and sphalerite ores is increasing significantly, but not expected to be fully exploited before 2050, and that current limitations in gallium supply are caused by production capabilities rather than global resources (Frenzel et al., 2016; Løvik et al., 2016). However, the current MFA literature does not quantify how supply chain resilience can be improved by domestic production and recycling.

Beyond MFA, critical materials research has utilized techno-economic assessment (TEA) to investigate economic performances of manufacturing processes to assess cost-competitiveness (U.S. Department of Energy, Mahmud et al., 2021). By analyzing the cost structure of production, TEAs can identify sensitivities to increase profitability or mitigate vulnerabilities to economic impacts, such as volatile raw material price developments. While TEAs are common for analyzing critical materials in manufacturing and recycling processes (Ciez and Whitacre, 2019; Gutsch and Leker, 2024), studies examining gallium production costs and recycling economics for gallium-containing EoL products remain scarce (Ravilla et al., 2024; Reese et al., 2019; Redlinger et al., 2015). Commercial-scale gallium recycling from EoL products does not currently occur, though some processes have been validated in a lab setting (Swain et al., 2015; de Oliveira et al., 2021; Ueberschaar et al., 2017; Liu et al., 2022; Zheng et al., 2023; Zhan et al., 2020).

Our MFA focuses on quantifying U.S. gallium flows from raw material import to EoL waste streams in 2023 to highlight U.S. gallium supply chain vulnerabilities. We then model multiple, alternative domestic gallium supply scenarios (domestic primary production and domestic EoL product recycling) and show the impact on reducing import reliance of raw gallium metal under different gallium demand growth scenarios by 2035. The domestic primary production scenarios focus on the two gallium production pathways, refinement from Bayer liquor and ZLR, selected for their commercial relevance and potential feedstock availability in North America. Based on findings in our MFA for the potential primary supply of gallium via these two pathways, we developed techno-economic models for gallium production costs from each feedstock source. For the Bayer liquor pathway, we modeled gallium extraction from the waste stream of an existing alumina facility in Louisiana (Zheng et al., 2023) which currently produces alumina without recovering gallium. For the ZLR pathway, we used the planned Nyrstar facility in Tennessee (Fitch, 2023; Brown, 2023; Williams, 2022) as a reference plant to establish baseline capital and operating parameters, then modeled how these would scale to process zinc residues from an existing facility in British Columbia (Trail Operations). This approach allows us to evaluate near-term production possibilities that leverage existing North American industrial infrastructure. Our analysis thus addresses current gaps in the MFA and TEA literature by developing detailed cost models for realistic domestic supply scenarios.

2. Methods

2.1. Material flow analysis: U.S. gallium life cycle flows

In this study, we use a static material flow analysis (MFA) to show gallium flows into and within the United States for 2023 to understand vulnerabilities in gallium supply chains and derive scenarios for alternative supplies. Further, we use a dynamic MFA from 2023 to 2035 to analyze alternative supply scenarios and determine the resulting import reliance. Modelling EoL product flows allows tracing annual EoL gallium flows that represent secondary gallium supply potentials after EoL. The static MFA for 2023, the dynamic MFA up to 2035 and the EoL model applied here comprise a total of five phases within the life cycle of gallium. These include: (1) the mining of primary raw material, (2) gallium refining, (3) compound fabrication, (4) intermediate product manufacturing, and (5) end-product use or application (Løvik et al., 2015; Frenzel et al., 2016). In each life-cycle stage, U.S. imports and exports of gallium containing compounds, intermediate products etc. are quantified based on data of the trade databases UN Comtrade Database and the United States International Trade Commission (ITC) DataWeb and individual material intensities (gallium contents) for compounds, intermediate products and end-products.

In addition to these five life cycle phases, we model various waste management streams: recycling of new scrap during compound fabrication and intermediate product manufacturing, EoL products, and final losses to landfill. We include multiple parameters in our alternative supply scenarios that influence future domestic gallium supply. First, we analyze gallium consumption growth scenarios through 2035 to understand their effects on overall future U.S. gallium demand and import reliance. Second, we combine these demand growth scenarios with increasing EoL product recycling rates to assess how secondary supply could reduce import reliance. Third, we evaluate scenarios for improving supply chain resilience based on findings from our static 2023 MFA, including enhanced compound fabrication efficiencies, improved intermediate product manufacturing efficiencies, and higher new scrap collection rates. Finally, we quantify how domestic primary gallium production could reduce import reliance across several production scenarios.

In the MFA, all gallium material flows from mining, import, refining, compound fabrication, intermediate product manufacturing to end-product use/application and waste management streams are represented by the absolute gallium content (in kg), which flows into and out of the corresponding life-cycle stages. The individual stocks and flows are calculated by the absolute gallium consumption (in kg) and consumption shares (in %) of individual compounds, intermediate products and end-products applications. In addition, we consider the processing efficiencies and product yields in the individual life cycle or value chain stages as well as new scrap generation and EoL collection and recycling rates (in %). The flows between each life-cycle stage in this MFA are determined by applying mass balance calculations based on absolute gallium content (D.J. Bauer et al., 2023; Han et al., 2024). Therefore, within each life-cycle stage, the inflows (feedstock, import) equal outflows (output, export, losses) plus stock increase according to Eq. (1):

$$Ga_{i,j,t}^{feedstock} + Ga_{i,j,t}^{import} = Ga_{i,j,t}^{output} + Ga_{i,j,t}^{export} + Ga_{i,j,t}^{losses} + Ga_{i,j,t}^{stock} \quad (1)$$

where i represents the considered life-cycle stage; j is the type of gallium metal or gallium-containing compound, intermediate product or end-product; t is the considered year of analysis; $Ga_{i,j,t}^{feedstock}$ (in kg) and $Ga_{i,j,t}^{import}$ (in kg) are the absolute feedstock or input from prior life-cycle stages and the absolute imports of gallium into the respective life-cycle stage; $Ga_{i,j,t}^{output}$ (in kg), $Ga_{i,j,t}^{export}$ (in kg) and $Ga_{i,j,t}^{losses}$ (in kg) denote the absolute gallium output into the subsequent life-cycle stage, absolute gallium exported at the stage and absolute losses during processing within the life-cycle stage, e.g., in compound fabrication or intermediate product manufacturing processes; and $Ga_{i,j,t}^{stock}$ (in kg) is the absolute increase in stocks, for example during the in-use phase of gallium-containing end-products.

Detailed information on data and parameter settings for the U.S. gallium MFA across all life cycle stages applied in this study (primary raw material mining and refining; compound fabrication; intermediate product manufacturing; end-product use/application; waste streams) are shown in the Supplementary Information Table 1.1–1.15. Data on EoL modelling and the alternative scenario analysis are shown in the Supplementary Information Table 1.16–1.18.

2.2. Techno-economic assessment: U.S. primary gallium production sources

Techno-economic assessment (TEA) provides a structured methodology for evaluating the commercial viability of process technologies by connecting technical performance parameters to their economic implications. These models begin with the technical production process,

mapping the material and energy inputs for each process step, as well as the required capital goods and operational labor. Our analysis follows a bottom-up modeling approach consisting of three main components: (1) a process model that captures material and energy flows, equipment requirements, and key operating parameters, (2) a cost model that translates these technical specifications into capital and operating expenses, and (3) a financial model that combines these elements to calculate levelized production costs under different scenarios.

Techno-economic modelling is commonly used to assess the economic viability of both energy (Kapila et al., 2017; Yu et al., 2024) and chemical (Biddy et al., 2016; Van Yken et al., 2023; Jouny et al., 2018) processes. While firm-level analyses often focus on profitability metrics that incorporate market prices and company-specific financial parameters, we calculate levelized cost of production to provide a more fundamental technical-economic benchmark. This approach allows us to evaluate the underlying cost structure of the technology independent of volatile commodity market conditions or firm-specific assumptions about required rates of return. In our analysis, market prices are used only for post-hoc benchmarking and do not influence any cost calculation.

We calculated levelized-cost-of-production (*LCoProd*) for each of our modeled processes according to the Eq. (2):

$$LCoProd = \sum_{t=0}^{n} \frac{\frac{Cap_t + Op_t}{(1+r)^t}}{\frac{Prod_t}{(1+r)^t}} \quad (2)$$

where t is the year in a project; n is the lifespan of the project; Cap_t is the capital expenditure in year t; Op_t is the total operating cost in year t; $Prod_t$ is the total output in year t; and r is the discount rate. Detailed discussion of our specific choice and derivation of core modeling parameters can be found in the Data Sources subsection in the Supplementary Information, but we will now overview our general approach to development of the model.

In some cases which applied across scenarios, such as discount rate, we parameterized values universally. Our parameter estimation followed a hierarchical approach: First, wherever possible, parameters were calculated directly from our physical process model on a per-unit-of-production basis. When process-based calculations were not feasible, we sought empirical values from documented operations using the same production route. Only when neither process-derived nor empirical values were available did we draw from analogous production processes with similar technical characteristics. This methodology grounds our analysis in the physical and engineering constraints of the production system while maintaining transparency about parameter sources and uncertainty.

Our analysis focuses on two production routes selected for their commercial relevance and domestic feedstock availability. The Bayer liquor derived process represents the dominant commercial pathway for gallium production globally (Lu et al., 2017). For ZLR processing, we modeled a combined gallium-germanium production line (Liu et al., 2017; Liu et al., 2017; Liu et al., 2016), reflecting the approach of the planned Nyrstar domestic facility in Tennessee, USA (Fitch, 2023; Brown, 2023; Williams, 2022). These processes allow us to evaluate near-term domestic production possibilities that build on existing industrial capabilities and feedstock streams.

The ZLR process produces both gallium and germanium as co-products, requiring a methodological choice in cost attribution. While some process costs (such as specific precipitation reagents) can be uniquely attributed to individual products, most capital costs and operating steps jointly contribute to both outputs. For such shared costs, several attribution approaches exist. Economic allocation based on market values is common in detailed financial models, while another approach involves valorizing co-products at assumed prices. We instead chose to attribute shared costs based on mass yield ratios, an approach more commonly seen in life-cycle assessment (Mahmud et al., 2021; Azapagic and Clift, 1999). This mass-based allocation maintains our analysis's grounding in physical process (Ijassi et al., 2021), while avoiding the introduction of price parameters that often become dominant sensitivities in economic allocation models. When directly comparing production pathways and analyzing future demand scenarios, we present the unallocated levelized costs (treating gallium as the sole product). For our base case analysis of the ZLR pathway, we also present costs allocated by mass yield ratio, allowing comparison of the pathway both in isolation and accounting for its co-product value.

We evaluated three scenarios for each production pathway. Our baseline scenario sizes the plant to recover all economically harvestable gallium from the host facility's rated capacity of alumina or zinc production. For the ZLR pathway, this means scaling to fully recover whichever co-product (gallium or germanium) has the larger mass yield. We then modeled three total scenarios reflecting potential trade restrictions or policy environments limiting production to domestic consumption. The first constrains addressable market exclusively to projected U.S. demand under moderate growth (6.5 % CAGR), while maintaining the capability to harvest all available gallium. The second constrains addressable market to exclusively meet projected U.S. demand under high growth (9.5 % CAGR), while maintaining the capability to harvest all available gallium The thirds scenario constrains the addressable market to moderate growth U.S. demand, and scopes initial plant capacity to meet projected 2035 U.S., allowing us to evaluate the cost implications of building ahead of demand growth. All growth rates are derived from DOE projections and historical trends in semiconductor applications, while the production parameters incorporate empirically measured yields from industrial operations (see SI Tables 2.1–2.6 for detailed process parameters and their sources). These alternative scenarios explore how production costs might shift under policy environments where tariffs, export restrictions, or other trade barriers limit producers to domestic markets.

3. Results

3.1. U.S. gallium material flow analysis in 2023

Fig. 2 shows U.S. gallium flows in 2023, which is based on mass balance calculations, U.S. market shares, trade data, and material intensities of each gallium life cycle stage, as well as on EoL model calculations (see Methods and Supplementary Information for further details). In 2023, the total U.S. gallium consumption of approximately 19 t (in compound fabrication stage) was imported from other countries (e.g., China, Japan, Germany, Canada), indicating an import reliance of 100 % (see Fig. 1: no primary gallium is produced by the United States). A small share of consumption was covered using gallium stocks, which historically has also been imported, as the United States has not produced primary raw gallium since 1987. The largest imports in 2023 included the most important materials in the gallium value chain, such as low-purity (99 to 99.99 % (2–4 N) gallium content) and high-purity (6–7 N) raw gallium (around 11.4 t in total) and GaAs (around 4.6 t of gallium content), in addition to the import of gallium in individual intermediate products such as LEDs or NdFeB magnets.

Overall, the United States imported around 22.4 t of gallium along the entire value chain in 2023, and exported approximately 6.4 t of gallium in intermediate and final products. In 2023 Gallium was primarily used in the form of GaAs wafers (around 63 % of total gallium consumption in compound stage) and ICs (74 % of total gallium consumption in intermediate product stage; without trade). Within the processes along the U.S. gallium value chain, around 19.8 t of gallium scrap were generated in 2023, of which 11.2 t (58 %) could be recycled as new scrap (gallium-intensive processing scrap occurred during refining, compound fabrication and intermediate product manufacturing, as opposed to old scrap from EoL) and reused as new feedstock for refining, compound fabrication and intermediate product manufacturing. The remaining gallium in production scrap ended up in landfills. For final disposal, we found that in 2023 about 10.5 t of

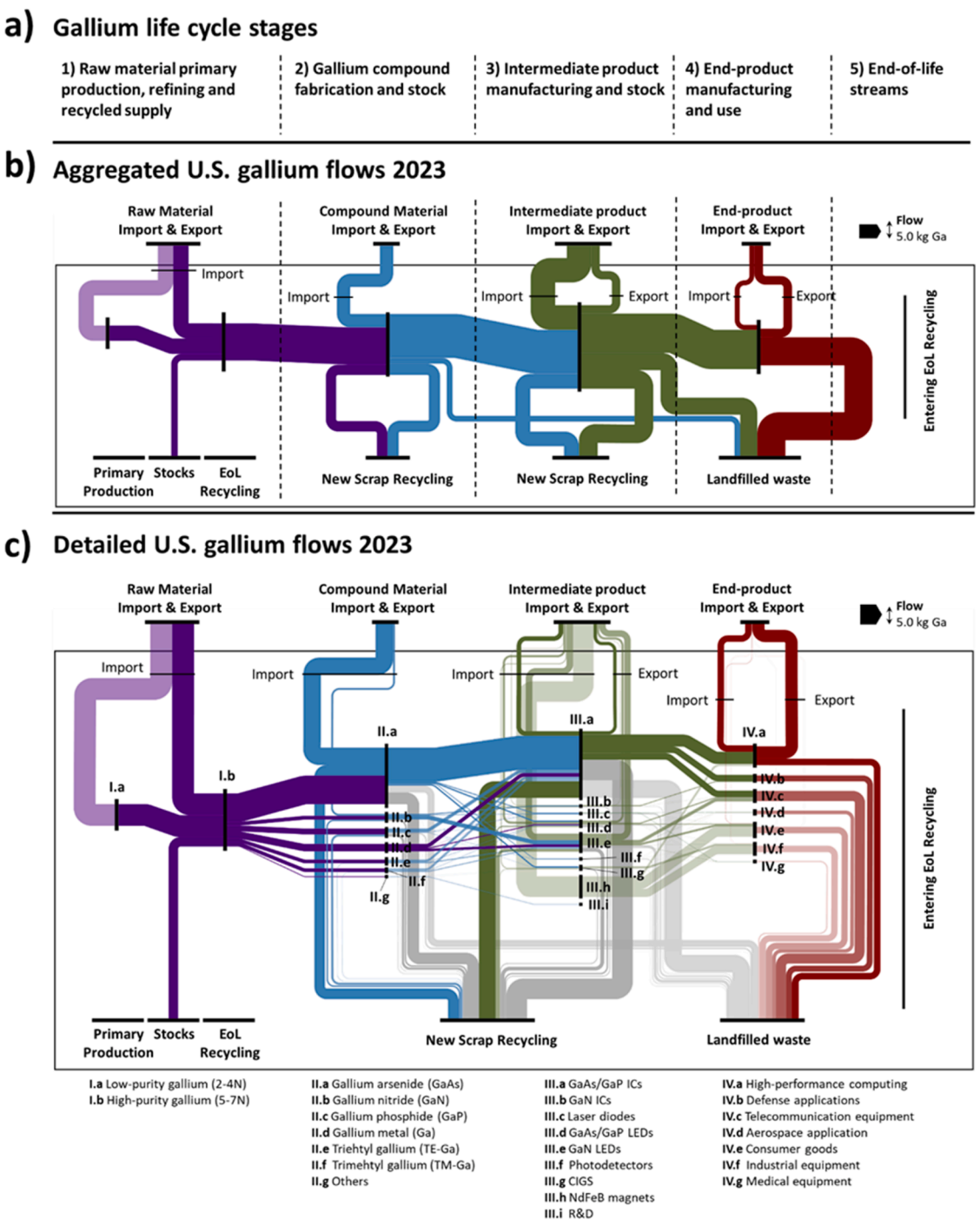


Fig. 2. Gallium life cycle stages and U.S. gallium flows in 2023. a) Gallium life cycle stages analyzed in this study. **b)** Aggregated level of U.S. gallium flows in 2023. **c)** Detailed level of U.S. gallium flows in 2023, considering raw gallium, different gallium-containing compounds, intermediate products, and end-products occurring in the U.S. gallium ecosystem. Note: Flows in **b)** and **c)** represent total gallium content flows (in kg) between different life cycle stages and external trade partners. In 2023, no domestic raw material production and recycling of end-of-life gallium occurred within the United States.

gallium reached EoL, such as in mobile phones, laptops, solar cells or LED lighting. Since there are currently no facilities for recycling gallium and accordingly no domestic secondary gallium supply in the United States, this EoL gallium ended up as waste.

3.2. Alternative domestic supply scenarios to reduce import reliance by 2035

The 2023 U.S. gallium flows reveal vulnerabilities that could be mitigated through domestic feedstocks. We analyze the potential supply of these feedstocks in alternative supply scenarios. First, a substantial amount of EoL gallium indicates feedstock potential for recycling, rather than landfilling. Second, there is also significant potential for the development and scaling of domestic gallium production from current bauxite or sphalerite ore as an alternative raw material supply source. Furthermore, key production processes can be optimized to avoid losing valuable waste and enhance reusing gallium from process scrap.

To improve U.S. supply chain resilience and reduce import reliance on gallium metal, we investigated the impact of multiple alternative gallium supply scenarios, which are shown in Table 1, on future gallium

Table 1
Analyzed import reliance impact categories and parameter settings for basic and alternative gallium supply scenarios. Note: Scenarios assume sufficient up-scaling of recycling capacity to produce secondary gallium.

Import reliance impact category	Parameter	Basic parameter setting	Analyzed alternative scenarios and parameter settings by 2035
Gallium demand/ consumption	Compound annual growth rate (CAGR) of demand/ consumption/import	Baseline: 6.5 % per year	Slow: 3.5 % per year Aggressive: 9.5 % per year
Domestic primary gallium supply	Domestic gallium supply	Bayer liquor refinement process: 0 kg/year Zinc leaching residues (ZLR) refinement process: 0 kg/year	Bayer liquor refinement process: Lower bound: 24,200 kg/year; base case: 76,610 kg/year; upper bound: 100,810 kg/year Zinc leaching residues (ZLR) refinement process: Lower bound: 26,900 kg/year; base case: 95,650 kg/year; upper bound: 107,600 kg/year
Domestic secondary (recycled) gallium supply	EoL product recycling rates	No EoL product recycling currently: 0 % (for all products)	Increasing recycling rates through scaling recycling capacity and improved efficiency: 30 %, 60 %, 90 % (for all EoL products, or solely ICs/LEDs/solar cells in EoL products)
New scrap recycling	Collection rates of new scrap during compound fabrication and intermediate product manufacturing	GaAs: 63 % ICs: 54 % LEDs: 58 % CIGS (used in solar cells): 70 %	Increased new scrap collection rate scenarios: 90 % (for GaAs, ICs, LEDs, CIGS or all)
Fabrication/ manufacturing process yield	Yields of compound fabrication/intermediate product manufacturing processes	GaAs: 35 % ICs: 16 % LEDs: 28 % CIGS (used in solar cells): 45 %	Increased process yield scenarios: 90 % (for GaAs, ICs, LEDs, CIGS or all)

supply and demand in 2035. Building on gallium demand in 2023 (19 t), in our baseline scenario, gallium demand or consumption grows by a compound annual growth rate (CAGR) of 6.5 % each year as evaluated by the U.S. Department of Energy (Bauer et al., 2023), resulting in a gallium demand of 40.5 t by 2035. To account for demand growth uncertainty, we also investigate impacts in both slow (CAGR: 3.5 %) and aggressive (CAGR: 9.5 %) demand growth scenarios by 2035 as alternative scenarios. In addition, in the alternative recycled supply scenarios, we evaluate various potential EoL recycling rates of 30–90 % for specific and important products (baseline: 0 % for all products, as no EoL recycling is commercialized so far). Finally, we combine alternative assumptions for demand growth and EoL recycling rates with optimized supply chains scenarios. These scenarios are based on the optimization of new scrap recycling and production process yields, as these parameters mainly influence the EoL model (see Table 1: 'new scrap recycling' and 'fabrication/manufacturing process yields'). Additional information on our basic parameter settings of the MFA is presented in the methods section and the Supplementary Information.

Overall, we investigated two key supply sources for gallium: domestic EoL recycling for different products, and domestic primary production from the two gallium production pathways ZLR and Bayer liquor refinement, based on modelling process residue outputs from the zinc production facility in Tennessee and alumina production facility in Louisiana.

Fig. 3 shows the resulting raw gallium metal import reliance in 2035 for the alternative supply scenarios of domestic primary gallium production (a) and domestic gallium recycling from EoL products (b). The results indicate that the base case and upper bound scenarios of our two modelled gallium primary production facilities (Bayer liquor and zinc leaching residue refinement processes) can cover gallium demand in 2035 in all demand growth scenarios (Fig. 3a). The lower bound scenarios can only cover 60–66 % of gallium demand in the baseline demand growth scenario (6.5 % CAGR) in 2035, and only 43–48 % in the aggressive demand growth scenario (9.5 % CAGR).

As shown in Fig. 3b, the alternative supply scenarios of domestic gallium recycling from EoL products have the potential to reduce import reliance to maximal 31 % (recycling of all EoL products containing ICs, LEDs, solar cells and others; 90 % gallium recycling rate; increased process yields of all product manufacturing). The intensified recycling of EoL products containing LEDs or solar cells can only marginally supply secondary gallium compared to demand, resulting in the reduction of a maximum of 2 % for all scenarios of solar cells recycling and 8 % for all scenarios of LED recycling. Import reliance among all recycling scenarios cannot be improved significantly (2–3 %) by simultaneously increasing fabrication process yields or new scrap collection rates of GaAs, a key compound in the U.S. gallium ecosystem. However, the optimization of all processes and collection rates has a substantial impact on recycled supply and can reduce import reliance to 44 % and 53 % (90 % recycling of all products), respectively, compared to the resulting import reliance of basic parameter settings (66 %), assuming a baseline gallium demand CAGR of 6.5 %.

3.3. Techno-economic assessment of U.S. primary gallium production: baseline scenario

Our TEA focuses on the two alternative primary gallium production routes selected for their commercial relevance and domestic feedstock availability (see Fig. 3a). The Bayer liquor derived process flow diagram (Lu et al., 2017) represents the dominant commercial pathway for gallium production globally (Lu et al., 2017). For ZLR processing, we modeled a combined gallium-germanium production line (Liu et al., 2017; Liu et al., 2017; Liu et al., 2016; Meshram and Abhilash, 2022), reflecting the approach of the planned Nyrstar domestic facility in Tennessee (Fitch, 2023; Brown, 2023; Williams, 2022). These processes allow us to evaluate near-term domestic production possibilities that build on existing industrial capabilities and feedstock streams.

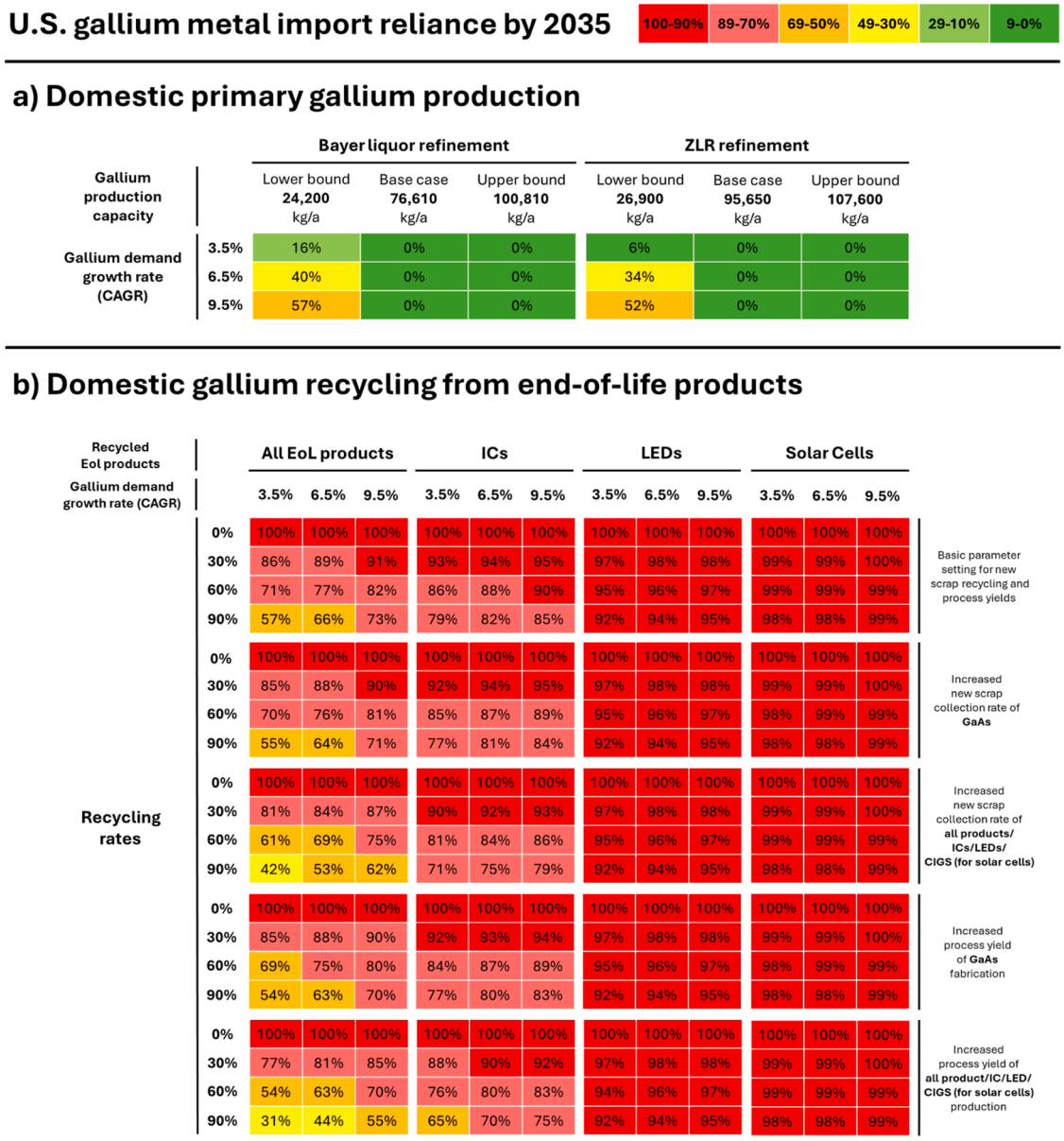


Fig. 3. Raw gallium metal import reliance by 2035 for alternative domestic supply scenarios in the three gallium demand growth scenarios (3.5 %, 6.5 %, and 9.5 % CAGR for 2023–2035). a) Alternative supply scenarios for domestic primary raw gallium production through a modelled Bayer liquor refinement process (for existing U.S.-located alumina production facility in Louisiana) and a modelled zinc leaching residue (ZLR) refinement process (for planned process additions of U.S.-located zinc refining facility in Tennessee). b) Alternative supply scenarios for domestic gallium recycling from end-of-life products (increasing gallium recycling rates of end-of-life products for all products, ICs, LEDs, or solar cells) and applied basic parameter settings and optimization scenario parameter settings of increased new scrap collection rates and increased process yields. Note: Import reliance calculations are based on the comparison of annual raw gallium demand/consumption and raw gallium supply by domestic gallium recycling or primary production and exclude consumption after trades in intermediate and final products life cycle stage; all EoL products include all modeled gallium-containing products in this study, while ICs, LEDs and solar cells account for approximately 75 % of gallium-containing EoL products in 2035.

Schematic process flow diagrams for both pathways (Bayer liquor and ZLR refinement) applied in this study are shown in the SI Fig. 1.1 and 1.2.

Our modeling approach for estimating recoverable gallium resources uses conservative assumptions to address uncertainty in byproduct material extraction. For both pathways, we established baseline estimates using empirically measured average values from literature for key parameters. These calculations incorporate multiple sequential factors: gallium concentration in the original ore, annual feedstock processing volume, the fraction of gallium that transfers to the intermediate process stream (Bayer liquor or ZLR), and the economically achievable recovery efficiency from that stream. For conservative lower bounds, we deliberately selected the lowest reported values from literature for each of these parameters in the calculation chain, which produced a conservative estimate of 24.2 t of economically harvestable gallium per year in the Bayer case and 26.9 t in the ZLR case. This approach ensures our sensitivity analysis accounts for worst-case scenarios while remaining grounded in empirical data. Detailed calculations of these bounds, including all parameter values and their sources, are provided in the SI: Recoverable Resources.

With all costs combined, and discounting any germanium, a co-product when recovering gallium from ZLR, first-year operating costs for recovering gallium from Bayer liquor are 181.27 $/kg gallium and 277.88 $/kg gallium for the ZLR pathway, as shown in Fig. 4 (sum of

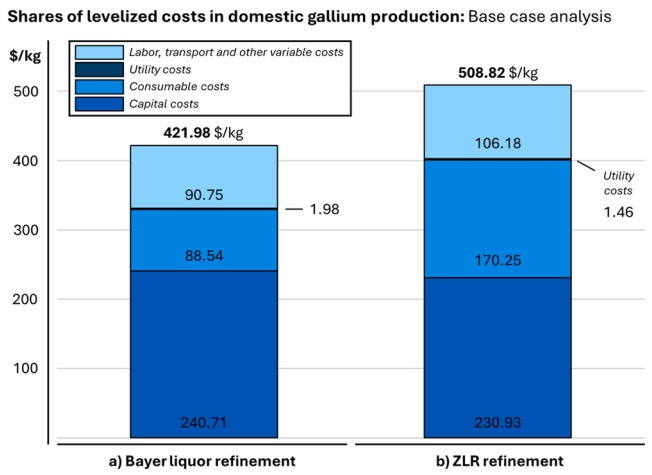


Fig. 4. Levelized gallium production costs in base case scenario. a): Cost structure of gallium production from Bayer liquor feedstock, normalized to dollars per kilogram of gallium produced. **b):** Cost structure of gallium production from zinc leaching residue (ZLR) feedstocks, normalized to dollars per kilogram of gallium produced. Total levelized costs are 421.98 $/kg for the Bayer liquor pathway and 508.82 $/kg for the ZLR pathway. While capital costs dominate both processes, the ZLR pathway incurs notably higher consumables costs (170.25 $/kg vs 88.54 $/kg). Note: All costs exclude germanium co-production in the ZLR process; values represent base case scenarios for brownfield installations at existing refineries.

non-capital costs). Total levelized cost for the baseline case, which excludes any consideration of germanium co-production, is 421.98 $/kg gallium from the Bayer liquor feedstock, and 508.82 $/kg gallium for the ZLR production pathway as shown. The composition of these levelized costs is shown in Fig. 4. It is noteworthy that in each case, upfront capital comprises the largest share of levelized cost of production. However, this is consistent with cost distributions amongst other mining and refinement facilities.

Contrastingly, when accounting for germanium co-production, the economics of the ZLR pathway improve markedly, with levelized costs dropping to 295.93 $/kg for gallium and 257.58 $/kg for germanium. The production capacity of either pathway would significantly exceed current U.S. domestic demand. The Bayer liquor refinement facility could produce 76.61 t of gallium annually, while the ZLR pathway could yield 95.65 t These volumes dwarf both U.S. demand in the wake of Chinese restriction of exports of 19 t/a (circa 2023 (United States Geological Survey, 2023)) and the previous baseline consumption of 36 t/a (circa 2014 (United States Geological Survey, 2014)). All of these baseline scenarios assume liquid global gallium and germanium markets in which the facility could sell all produced metal.

However, comparing our derived levelized primary gallium production costs via both pathways to levelized gallium recycling costs, the modeled primary production costs show significant cost advantages. For example, although still limited, prior analysis calculated levelized gallium recycling costs up to 3451 $/kg based on recycling gallium from EoL CIGS-based solar cells (Redlinger et al., 2015).

3.4. *Alternative scenarios: impact of market-driven production capacity scaling*

Production scenarios targeting only domestic demand result in higher levelized costs compared to baseline scenarios where full production can be sold into the global market, as illustrated in Fig. 5. We modeled three constrained scenarios: (1) full-scale plants limited to domestic sales under baseline demand growth (6.5 % CAGR), (2) full-scale plants with high domestic demand growth (9.5 % CAGR), and (3) plants sized specifically to meet projected 2035 domestic demand. Under baseline domestic growth, levelized costs increase substantially to 663.97 $/kg for the Bayer pathway and 864.50 $/kg for the ZLR pathway. Higher demand growth moderates these costs somewhat to 568.11 $/kg and 720.65 $/kg respectively. Interestingly, when plants are sized to match 2035 projected demand rather than maximum feedstock recovery, the two pathways achieve near cost parity: 664.93 $/kg for Bayer liquor and 673.79 $/kg for ZLR.

Capital costs dominate the levelized cost structure, making plant capacity optimization the most critical factor in achieving economic

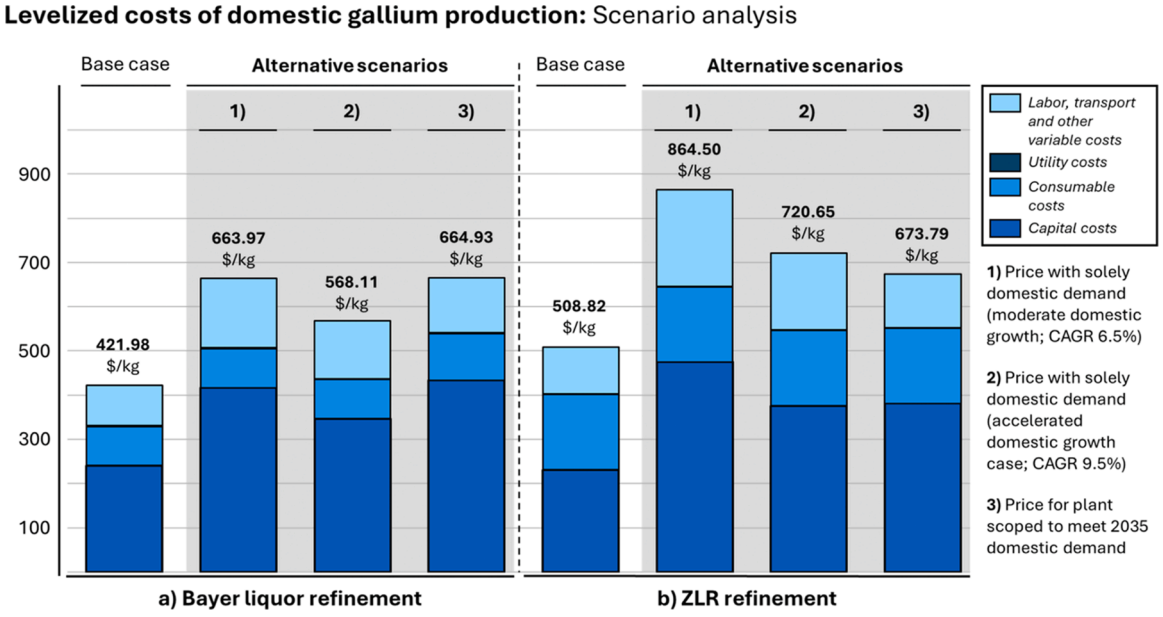


Fig. 5. Levelized gallium production costs in market-driven capacity scaling scenarios. Levelized production costs ($/kg gallium produced) across four scenarios for both Bayer liquor (a) and zinc leaching residue (ZLR) (b) refinement pathways are shown, excluding germanium revenue. The baseline case shows ZLR costs (508.81 $/kg) exceeding Bayer liquor costs (421.99 $/kg). When production is constrained to serve only domestic demand, costs increase substantially for both pathways, reaching 864.50 $/kg for ZLR and 663.97 $/kg for Bayer liquor. Under a high domestic growth scenario, costs moderate slightly to 720.65 $/kg and 568.11 $/kg respectively. Plants sized to meet projected 2035 baseline domestic demand show intermediate costs of 673.79 $/kg for ZLR and 664.93 $/kg for Bayer liquor.

viability. The relationship between plant scale and costs exhibits complex interactions due to economies of scale. For instance, sizing a ZLR plant to recover the upper-bound estimate of available gallium (107.6 t) would yield a levelized cost of 483.15 $/kg, while a 20 % reduction in capital intensity would lower costs to 462.62 $/kg. The relative importance of other cost drivers differs between pathways. For the ZLR process, reagent costs represent the second most significant operating cost sensitivity, while the Bayer pathway shows roughly equal sensitivity to both reagent costs and labor/fixed costs. Both processes prove relatively insensitive to utility price fluctuations due to their modest energy requirements, with utility costs comprising <1 % of total levelized costs. A full sensitivity analysis, with tornado plots illustrating the effects of varying capital intensity, operating costs, recoverable resources, or discount rate is available in the SI.

The cost implications of our market-restricted scenarios reveal important insights into production economics. When production is constrained to serve only domestic markets, costs increase dramatically, reaching 663.97 $/kg for the Bayer pathway and 864.50 $/kg for ZLR. This significant cost penalty under domestic-only scenarios highlights the economic challenges of geographically restricted production. Our analysis suggests that access to larger markets could substantially improve production economics.

From a technical feasibility perspective, our analysis indicates robust domestic production potential. Even under the conservative modeling assumptions outlined above, the harvestable gallium from a single plant using either feedstock would exceed current U.S. demand. Lower bound estimates for both feedstocks (Bayer liquor: 24.2 t/a; ZLR: 26.9 t/a) substantially exceed current annual U.S. consumption. More probable baseline estimates dwarf both current demand and pre-restriction consumption levels, suggesting that securing domestic supply is technically feasible with existing feedstock resources.

The dominance of capital costs in determining levelized cost of gallium suggests targeted policy interventions could effectively support supply chain diversification. Since our results suggest a single facility could robustly meet domestic demand, capital cost reduction policies could be relatively focused. To illustrate this, we modeled a 120 million USD production grant or tax incentive, scaled to match a modest single-facility CHIPS Act incentive (Broas, 2024). This scenario dramatically improves the production economics: the Bayer liquor pathway's levelized cost drops to 291.60 $/kg Ga, while the ZLR pathway achieves 399.31 $/kg gallium without co-product allocation, or 295.93 $/kg gallium and 257.78 $/kg germanium with allocation. These reduced costs would provide greater resilience against price volatility and represent a potentially cost-effective policy intervention for securing domestic supply.

4. Discussion

4.1. Enhancing U.S. gallium supply chain resilience: scenario implications

The MFA applied in this study reveals significant vulnerabilities in U.S. gallium supply chains, characterized by a 100 % import reliance of raw gallium metal. Based on these findings, we show in various scenarios how EoL product recycling and domestic primary production of gallium can make U.S. supply chains more resilient by reducing import reliance of raw gallium metal by 2035.

The results of these scenarios show that extending both existent alumina and zinc domestic primary production facilities through additional processing steps to refine gallium from process waste or residue can supply >100 % of U.S. gallium demand in 2035 in our baseline growth scenario. Scenarios for recycling EoL products increases secondary gallium supply of up to 56 % of U.S. demand in 2035 under optimal conditions in the baseline growth scenario, indicating a significant future supply potential.

Although there is still no commercial gallium recycling from EoL products, lab-scale research shows recycling rates and product purities above 90 % for gallium recovered from various end products (Reese et al., 2019; Redlinger et al., 2015; Swain et al., 2015; de Oliveira et al., 2021; Ueberschaar et al., 2017; Liu et al., 2022). This provides a foundation for eventual scale-up to increase domestic supply, but will likely take several years to reach commercial maturity. Nonetheless, the results in this analysis show that focusing on individual recycling processes for end-products such as chips (ICs) in mobile phones or laptops can make a significant contribution to domestic supply alternatives in the long term, and further function as an alternative source of other important raw materials, such as indium from CIGS-based solar cells.

Compared to domestic EoL product recycling, our MFA shows that U.S. primary gallium production has a much higher potential to cover future demand. The U.S. primary raw gallium production pathways modeled here are based on existing plants that produce alumina and zinc, processes from which gallium is already extracted as a by-product industrially. Thus, the technologies used in these processes are well-known and mature, and their implementation is significantly de-risked relative to recycling.

Despite the analysis showing that domestic primary supply can cover demand among most scenarios, however, our scenario analyses are timely limited to 2035. The relevance and demand for gallium is expected to increase further after 2035, as the substitutability of gallium in core technologies such as LEDs, chips, EVs, wind turbines, or solar cells is low, and the demand for these technologies are expected to increase against the background of gallium use in various increasingly important applications. Resilient supply chains may therefore have to ensure the ability to meet gallium demand that continues to rise after 2035. Domestic production strategies that combine the alternative supply scenarios for domestic production and recycling outlined here can therefore significantly reduce import reliance in the long term after 2035. In addition, the analysis of import reliance in this study refers to the consumption of raw metal gallium in the upstream processes of the U.S. value chain in refining and compound fabrication. To become more independent and resilient in downstream processes, such as intermediate or end-product manufacturing, production capacities must also be expanded and utilized efficiently. This requires an even higher demand for gallium supply, which can be covered by domestic production and recycling.

4.2. Cost-competitiveness and policy levers

Whereas prior literature shows significantly higher gallium production costs (e.g., 3451 $/kg from EoL CIGS-based solar cells) compared to primary production, our cost analysis results in a potential cost-competitiveness of primary gallium production via Bayer liquor or zinc leaching residue refinement pathways. Based on findings in the MFA for potential primary gallium sources in the United States, we assessed U.S. gallium production costs by techno-economic modelling. In our base case cost scenario, the Bayer liquor process achieves levelized costs of 421.98 $/kg gallium and the ZLR process (with mass-based co-product allocation) reaches 303.24 $/kg gallium.

The relationship between modeled production costs and historical market prices reveals critical insights about the economic viability of domestic gallium production. Our analysis suggests that U.S. primary production pathways could potentially be competitive in the current high-price conditions, with market prices of approximately 455 $/kg gallium and 2875 $/kg germanium in October 2024 (United States Geological Survey, 2014). We note that costs are only illustrative, not an input variable to any model. However, excluding co-product allocation of germanium would result in levelized production costs (508.82 $/kg) above current market prices and our domestic demand growth scenarios show another increase in levelized production costs (see Fig. 5). From industry perspective, these higher costs may still outweigh the significance of supply risks given current market conditions characterized by high country concentration, price control of individual stakeholder, and import reliance. In addition, though gallium is a critical material in

numerous technologies, the small gallium material intensities in intermediate (e.g., 0.00685 wt. % in LEDs (Gao et al., 2024)) and final products (e.g., 2.14 g/unit in NdFeB magnets for average electric vehicles (Gao et al., 2024)) may not primarily drive total product costs, further lowering impacts of higher domestic gallium production costs on feasibility of industrial manufacturing.

This analysis also illuminates why domestic production has historically been limited. Pre-trade restriction gallium prices (approximately 122.50 $/kg in October 2016) fall significantly below the levelized cost of production for either pathway, even under optimal conditions. This historical price environment helps explain the concentrated nature of global gallium production, the ability of dominant producers to rapidly increase supply and drive down market prices has created significant investment uncertainty for potential new market entrants The substantial gap between historical prices and sustainable production costs suggests that market forces alone may be insufficient to drive supply chain diversification, but valuation of reliability and resilience of supply could justify investments.

Since recycling gallium has not been economically feasible so far, there is no industrial-scale recycling of any gallium from EoL products, currently. Complexity in the manufacturing and design of the products, as well as the variety of materials that are used in small quantities, pose challenges for the scaling and profitability of recycling processes. In addition, there are other factors that are necessary for realizing large-scale recycling, such as new infrastructure (e.g., collection facilities, sorting technologies, and reverse logistics from collection to recycling facilities), product quality and management of competitive long-term capital and operating costs.

4.3. Global context and future work

Primarily, the results of the MFA and TEA in this study show how domestic primary production and recycling can strengthen the resilience of the gallium supply chain in the United States. However, this study also aims to encourage further research on enhancing supply chain resilience of gallium and other critical materials in other regional as well as global contexts.

Considering the potential of domestic primary production in other countries, Fig. 1 implies that countries such as, for example, Australia, Indonesia, Brazil, or India hold large deposits of gallium-containing bauxite or zinc, but, like the United States, are heavily dependent gallium imports from China's due to its gallium refining market dominance. Especially against the background of China's recent gallium (and other materials) export restrictions, future research, therefore, should apply methods and findings presented in this study to further investigate potentials to reduce gallium (or and other materials) import reliance in various countries, as well as explore cost-competitiveness of large-scale primary gallium production and refining compared to dynamic global market conditions.

The production potential of the Pacific and Oceania regions merits specific consideration. Both Indonesia and Australia have existing robust mining and refining infrastructure for the relevant feedstocks (Majumder, 2025; Young, 2025). Both the sphalerite (Huston and Bastrakov, 2024) and bauxite (Yellishetty et al., 2017) in the region show promise in terms of raw available gallium and germanium. Further study precisely characterizing the recoverable material in the commercially utilized ores could further reduce uncertainty. Assuming the same concentration of gallium in the ore as our baseline case, the five commercial alumina refineries and one zinc refinery in Australia could combine to produce approximately 1085 tons of gallium per annum. Under the same assumption, the three Indonesian alumina refineries could harvest 275 tons of gallium annually. Recent commercial exploration suggests that some Australian ores are richer in gallium than average (Teramoto, 2025), demonstrating the value of accurately characterizing the relevant ores. The Australian government is undertaking such characterization efforts through Geoscience Australia (Australia, 2025). Given the resource potential and political alignment between these Pacific states, future research should model their production costs in detail.

Furthermore, based on the increasing importance of gallium application in chips (i.e., ICs), LEDs, solar cells, or permanent magnets and gallium's low substitutability, future research might expand the combined MFA and TEA approach presented in this study to investigate other influential, downstream economic effects of gallium production and refining market entry, such as comprehensive regional or national welfare analysis or implications on international critical material trades and policies.

Next to exploring domestic sources, this study shows that domestic recycling can be a potential major gallium supply source. However, by comparing our derived primary gallium production costs with initial results for levelized cost analyses for gallium recycling, primary production indicates major cost advantages, which illustrates the challenge of viable recycling of complex gallium-containing products at nascent recycling technology development stages. So far, only limited research has been performed on gallium recycling costs for EoL products, and further investigations into gallium recycling costs are needed with upcoming new and improved recycling processes to fully explore the potential of recycling as a viable alternative supply source.

Finally, the case of gallium in the United States reveals high supply chain vulnerabilities, which result in substantial supply risks. Foremost, this study focuses on reducing import reliance as one potential measure to reduce supply risks, although a critical materials' supply risk presents a more complex and multi-faceted concept, which needs to be investigated in-depth to exploit risk mitigation strategies. However, our analysis of the U.S. gallium supply chain by MFA and TEA may function as a base to characterize and quantify critical material supply risks, and to further derive supply risk mitigation strategies for gallium and other critical materials.

5. Conclusion

Critical materials, such as gallium, are characterized by increasing supply risks, prompting a renewed emphasis on improving supply chains for industry and policymakers. In this study, using U.S. gallium flows as a case, we analyze current supply chains and identify opportunities to improve supply chain resilience by reducing import reliance of gallium metal. Our MFA on U.S. gallium flows in 2023 reveals significant supply chain vulnerabilities due to total import reliance on gallium metal, driven by high geographic concentration of mining and refining capacities, which threatens the deployment of gallium-based decarbonization technologies. Based on potential domestic gallium resources, we show that EoL product recycling and primary production of gallium can cover 50 % and 100 % of future gallium demand by 2035, respectively, depending on supply optimization scenarios. Finally, we evaluate domestic primary production costs of gallium. Applying a TEA based on conventional gallium production pathways (alumina and zinc leaching residue refining processes), we find that costs for domestic primary gallium production can be cost-competitive to import, i.e., global market prices, showing levelized costs of 422 to 509$/kg.

Funding

This work was supported by Lawrence Berkeley National Laboratory's Lab Directed Research and Development (LDRD) grant.

CRediT authorship contribution statement

Jannis Wesselkaemper: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Alex C. Newkirk:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Thomas P. Hendrickson:**

Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Nadiyah Helal:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Prakash Rao:** Writing – review & editing, Writing – original draft, Supervision, Resources, Funding acquisition, Conceptualization. **Sarah J. Smith:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Andrew Z. Haddad:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Brian Jaskula from the USGS for helpful conversations regarding the gallium supply chain. Lawrence Berkeley National Laboratory is supported by the U.S. Department of Energy under Contract No DE-AC02–05CH11231.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108436.

Data availability

Data will be made available on request.

References

Australia.G , "Critical mineral by-product potential," Geoscience Australia. Accessed: May 23, 2025. [Online]. Available: https://www.ga.gov.au/scientific-topics/minerals/australian-critical-minerals-research-and-development-hub/critical-mineral-by-product-potential.

Azapagic, A., Clift, R., 1999. Allocation of environmental burdens in co-product systems: product-related burdens (Part 1). Int. J. LCA 4, 357–369.

Baars, J., Domenech, T., Bleischwitz, R., Melin, H.E., Heidrich, O., 2021. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nat. Sustain. 4, 71–79.

Bauer, D.J., Nguyen, R.T., Smith, B.J., 2023a. Crit. Mater. Assess.

Bauer, D.J., Nguyen, R.T., Smith, B.J., 2023b. Crit. Mater. Assess.

Biddy, M.J., et al., 2016. The techno-economic basis for coproduct manufacturing to enable hydrocarbon fuel production from Lignocellulosic Biomass. ACS Sustain. Chem. Eng. 4, 3196–3211.

Broas, M. Biden-Harris administration announces preliminary terms with Polar Semiconductor to establish an independent American foundry. (2024).

Brown, C. Nyrstar Zinc in Clarksville could become nation's top source of 2 key minerals after China cuts off supply - ClarksvilleNow.Com. https://clarksvillenow.com/local/nyrstar-zinc-in-clarksville-could-become-nations-top-source-of-2-key-minerals-after-china-cuts-off-supply/(2023).

Cheng, A.L., Fuchs, E.R.H., Karplus, V.J., Michalek, J.J., 2024. Electric vehicle battery chemistry affects supply chain disruption vulnerabilities. Nat. Commun. 15, 2143.

Ciez, R.E., Whitacre, J.F., 2019. Examining different recycling processes for lithium-ion batteries. Nat. Sustain. 2, 148–156.

de Oliveira, R.P., Benvenuti, J., Espinosa, D.C.R., 2021. A review of the current progress in recycling technologies for gallium and rare earth elements from light-emitting diodes. Renew. Sustain. Energy Rev. 145, 111090.

Eggert, R., et al., 2016. Rare Earths: market disruption, innovation, and global supply chains. Annu Rev Env. Resour. 41, 199–222.

European Commission. Critical raw materials. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en (2024a).

European Commission. Critical raw materials. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en (2024b).

Fitch, A., 2023. Tennessee Zinc Smelter at the heart of global trade conflict. Wall Str. J.

Frenzel, M., Ketris, M.P., Seifert, T., Gutzmer, J., 2016. On the current and future availability of gallium. Resour. Policy. 47, 38–50.

Gao, Z., Geng, Y., Li, M., Liang, J.-J., Houssini, K., 2024. Tracking the global anthropogenic gallium cycle during 2000–2020: a trade-linked multiregional material flow analysis. Glob. Environ. Change 87, 102859.

Gutsch, M., Leker, J., 2024. Costs, carbon footprint, and environmental impacts of lithium-ion batteries – From cathode active material synthesis to cell manufacturing and recycling. Appl. Energy 353, 122132.

Haddad, A.Z., et al., 2023. How to make lithium extraction cleaner, faster and cheaper — In Six steps. Nature 616, 245–248.

Han, Z., et al., 2024. Tracking two decades of global gallium stocks and flows: a dynamic material flow analysis. Resour. Conserv. Recycl. 202, 107391.

Huang, Q., et al., 2022. The influence of Gallium doping on the magnetic performance and microstructure of Nd-Fe-B sintered magnets. J. Magn. Magn. Mater. 552, 169242.

Huston, D.L., Bastrakov, E., 2024. Germanium, indium, gallium and cadmium in zinc ores: a mineral system approach. Aust. J. Earth Sci. Nov.Accessed: May 21, 2025. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/08120099.2024.2423772.

IEA, 2024. Glob. Crit. Miner. Outlook 2024. https://www.iea.org/reports/global-critical-minerals-outlook-2024.

Ijassi, W., Ben Rejeb, H., Zwolinski, P., 2021. Environmental impact evaluation of co-products: decision-aid tool for allocation in LCA. Int. J. Life Cycle Assess. 26, 2199–2214.

Jouny, M., Luc, W., Jiao, F., 2018. General Techno-economic analysis of CO2 electrolysis systems. Ind. Eng. Chem. Res. 57, 2165–2177.

Kapila, S., Oni, A.O., Kumar, A., 2017. The development of techno-economic models for large-scale energy storage systems. Energy 140, 656–672.

Liu, F., et al., 2016. Extraction of gallium and germanium from zinc refinery residues by pressure acid leaching. Hydrometallurgy 164, 313–320.

Liu, F., et al., 2017b. Recovery and separation of gallium(III) and germanium(IV) from zinc refinery residues : part II: solvent extraction. Hydrometallurgy 171, 149–156.

Liu, F., Liu, Z., Li, Y., Wilson, B.P., Lundström, M., 2017a. Recovery and separation of gallium(III) and germanium(IV) from zinc refinery residues: part I: leaching and iron (III) removal. Hydrometallurgy 169, 564–570.

Liu, F.-W., et al., 2022. High-yield recycling and recovery of copper, indium, and gallium from waste copper indium gallium selenide thin-film solar panels. Sol. Energy Mater. Sol. Cells 241, 111691.

Løvik, A.N., Restrepo, E., Müller, D.B., 2015. The global anthropogenic gallium system: determinants of demand, supply and efficiency improvements. Env. Sci. Technol. 49, 5704–5712.

Løvik, A.N., Restrepo, E., Müller, D.B., 2016. Byproduct metal availability constrained by dynamics of carrier metal cycle: the gallium–Aluminum example. Env. Sci. Technol. 50, 8453–8461.

Lu, F., et al., 2017. Resources and extraction of gallium: a review. Hydrometallurgy 174, 105–115.

Lv, A., Munroe, T., 2024. China bans export of critical minerals to US as trade tensions escalate. Reuters.

Mahmud, R., Moni, S.M., High, K., Carbajales-Dale, M., 2021. Integration of techno-economic analysis and life cycle assessment for sustainable process design – A review. J. Clean. Prod. 317, 128247.

Majumder, Rupankar "Four existing alumina refineries may sustain Indonesia's bauxite ban; aluminium extrusion, profiles, price, scrap, recycling, section," Alcircle. Accessed: May 23, 2025. [Online]. Available: https://www.alcircle.com/news/four-existing-alumina-refineries-may-sustain-indonesia-s-bauxite-ban-93654?srsltid=AfmBOorO8e5SXeLKSmGXU-j0Zap4O3juuFU_v9FpJMku1tNptIrx8MLB.

Meshram, P., Abhilash, 2022. Strategies for recycling of primary and secondary resources for germanium extraction. Min. Metall. Explor. 39, 689–707.

Nassar, N.T., Shojaeddini, E., Alonso, E., Jaskula, B. & Tolcin, A. *Quantifying potential effects of China's gallium and germanium export restrictions on the U.S. Economy. Open-file report* https://pubs.usgs.gov/publication/ofr20241057 (2024) doi:10.3133/ofr20241057.

Ravilla, A., Gullickson, E., Tomes, A., Celik, I., 2024. Economic and environmental sustainability of copper indium gallium selenide (CIGS) solar panels recycling. Sci. Total. Environ. 951, 175670.

Redlinger, M., Eggert, R., Woodhouse, M., 2015. Evaluating the availability of gallium, indium, and tellurium from recycled photovoltaic modules. Sol. Energy Mater. Sol. Cells 138, 58–71.

Reese, S.B., Remo, T., Green, J., Zakutayev, A., 2019. How much will gallium oxide power electronics cost? Joule 3, 903–907.

Song, H., Wang, C., Sen, B., Liu, G.China Factor, 2022. Exploring the byproduct and host metal dynamics for gallium–Aluminum in a global green transition. Env. Sci. Technol. 56, 2699–2708.

Sun, X., et al., 2024. Reducing supply risk of critical materials for clean energy via foreign direct investment. Nat. Sustain. 7, 672–681.

Swain, B., et al., 2015. Recycling process for recovery of gallium from GaN an e-waste of LED industry through ball milling, annealing and leaching. Env. Res. 138, 401–408.

Teramoto, Shiba, 2025. New gallium discovery unveiled in Australasian metals' Bauxite project. Chemanalyst. Accessed: May 23,[Online]. Available: https://www.chemanalyst.com/NewsAndDeals/NewsDetails/new-gallium-discovery-unveiled-in-australasian-metals-bauxite-project-31855.

Trail Operations. *Teck Resour. Ltd.* https://www.teck.com/operations/canada/operations/trail-operations/.

U.S. Department of Energy. Life cycle assessment and techno-economic analysis training. *Energy.gov* https://www.energy.gov/eere/iedo/life-cycle-assessment-and-techno-economic-analysis-training.

Ueberschaar, M., Otto, S.J., Rotter, V.S., 2017. Challenges for critical raw material recovery from WEEE – The case study of gallium. Waste Manage. 60, 534–545.

United States Geological Survey. *Mineral commodity summaries 2014. Mineral commodity summaries* https://pubs.usgs.gov/publication/mcs2023 (2014) doi:10.3133/mcs2023.

United States Geological Survey. *Mineral commodity summaries 2023. Mineral commodity summaries* https://pubs.usgs.gov/publication/mcs2023 (2023) doi:10.3133/mcs2023.

United States Geological Survey, 2024. Miner. Commod. Summ. 2024. Miner. Commod. Summ. https://doi.org/10.3133/mcs2024. https://pubs.usgs.gov/publication/mcs2024.

Van Yken, J., et al., 2023. Techno-economic analysis of an integrated bio- and hydrometallurgical process for base and precious metal recovery from waste printed circuit boards. Hydrometallurgy 222, 106193.

Wesselkämper, J., Dahrendorf, L., Mauler, L., Lux, S., von Delft, S., 2024. Towards circular battery supply chains: strategies to reduce material demand and the impact on mining and recycling. Resour. Policy. 95, 105160.

Williams, C. Nyrstar plans expansion of Clarksville plant with $90 million germanium, gallium processing facility - ClarksvilleNow.Com. https://clarksvillenow.com/local/nyrstar-plans-expansion-of-clarksville-plant-with-90-million-germanium-gallium-processing-facility/(2022).

Yellishetty, M., Huston, D., Graedel, T.E., Werner, T.T., Reck, B.K., Mudd, G.M., Apr. 2017. Quantifying the potential for recoverable resources of gallium, germanium and antimony as companion metals in Australia. Ore Geol. Rev. 82, 148–159. https://doi.org/10.1016/j.oregeorev.2016.11.020.

Young, Asaesja, 2025. Critical minerals: the Quiet Achievers Gallium and Germanium. CSIRO. Accessed: May 23,[Online]. Available: https://www.csiro.au/en/news/All/Articles/2024/June/Critical-mineral-gallium-germanium.

Yu, Q., Hao, Y., Ali, K., Hua, Q., Sun, L., 2024. Techno-economic analysis of hydrogen pipeline network in China based on levelized cost of transportation. Energy Convers. Manage. 301, 118025.

Zhan, L., Zhang, Y., Ahmad, Z., Xu, Z., 2020. Novel recycle technology for recovering gallium arsenide from scraped integrated circuits. ACS Sustain. Chem. Eng. 8, 2874–2882.

Zheng, K., Benedetti, M.F., van Hullebusch, E.D., 2023. Recovery technologies for indium, gallium, and germanium from end-of-life products (electronic waste) – A review. J. Env. Manage. 347, 119043.