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Boundary Artifacts, Not Process Advantage, Explain Why Allocation Bias Makes Secondary Critical Mineral Recovery Look Greener Than Virgin Extraction

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Abstract

Life-cycle assessments comparing secondary critical mineral recovery, from electronic waste and industrial effluent, against virgin extraction are increasingly cited to justify recycling incentives and carbon-linked market access under regulations such as the European Union Critical Raw Materials Act and Battery Regulation. This paper argues that much of the reported carbon advantage of secondary recovery is an artifact of discretionary system-boundary and allocation choices rather than a stable process-level result. Reviewing published inventory data for gold recovery from waste electrical and electronic equipment and chromium recovery from tannery and electroplating wastewater, we show that the same underlying recovery chemistry yields carbon footprints spanning two to three orders of magnitude depending on whether a cut-off, avoided-burden, or Circular Footprint Formula allocation is applied. Reported secondary gold values range from approximately 40 to 57,900 kg CO2 equivalent per kilogram against a virgin benchmark near 30,000; chromium recovery via microbial fuel cell shows a saving of up to 97% under avoided-burden accounting that falls to 61.8% once allocated credits are withdrawn, with the pre-credit process itself a net emitter. We further show that avoided-burden accounting assumes near-complete displacement of virgin production, an assumption the empirical industrial-ecology literature does not support for analogous metals. We propose a minimum disclosure checklist, comprising allocation method, feedstock burden treatment, displacement assumption, and functional unit, for any carbon claim submitted in support of secondary critical mineral recovery under emerging regulatory frameworks, grounded in the requirements of ISO 14044, ISO 14067, and ISO 14064-3.

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1. INTRODUCTION

Carbon accounting is becoming a gatekeeping mechanism for critical mineral markets. The European Union Battery Regulation requires carbon footprint declarations for electric-vehicle and industrial batteries [1], and the Critical Raw Materials Act empowers the European Commission to set environmental footprint rules, including greenhouse gas emissions, for materials placed on the market [2]. Secondary recovery routes, drawing critical metals from waste electrical and electronic equipment or industrial effluent rather than ore, are widely presented as the lower-carbon alternative that these frameworks should reward.

This presentation rests on a methodological choice that is rarely disclosed alongside the headline number. Life cycle assessment offers at least three defensible ways to allocate the environmental burden of a material that enters or leaves a waste stream: a cut-off approach that charges only the recovery process itself and treats the incoming waste as burden-free; an avoided-burden or system-expansion approach that credits the recovery route with the impact of the virgin production it is assumed to displace; and the European Union's Circular Footprint Formula, which interpolates between the two using a discretionary allocation factor. Each is legitimate under the International Organization for Standardization framework for life cycle assessment [3]. Each produces a different number from the same physical process.

This paper examines two recovery routes, gold from waste electrical and electronic equipment and chromium from industrial wastewater, where published literature reports carbon footprints spanning two to three orders of magnitude for comparable underlying chemistry. We trace the spread to its methodological source, construct a boundary-sensitivity re-analysis using the European Union's own Circular Footprint Formula, and examine the displacement assumption embedded in avoided-burden accounting against empirical evidence from industrial ecology. We close with a minimum disclosure checklist intended to make secondary-recovery carbon claims auditable, grounded in existing International Organization for Standardization requirements rather than proposing a new standard.

2. METHODS

This is a comparative re-analysis of published, peer-reviewed life cycle inventory data rather than a primary inventory study. For each case, we identify the reported carbon footprint, the functional unit, the system boundary, and the allocation or crediting method used in the source study, then recompute or bound the result under the alternative allocation conventions permitted by ISO 14044 [3] and formalized in the European Union's Product Environmental Footprint guidance. Where a source study does not report results under multiple allocation conventions, we apply the Circular Footprint Formula documented by the European Commission's Joint Research Centre to the reported process-level data to estimate the range that alternative, equally defensible allocation choices would produce. Virgin-production benchmarks are drawn from independently published sources rather than the case-study papers themselves, to avoid circularity in the comparison.

3. RESULTS AND DISCUSSION

Case Study One: Gold Recovery from Waste Electrical and Electronic Equipment

Fritz and Schmidt [4] model pyrometallurgical gold recovery on the Kaldo-furnace route operated at an integrated Swedish copper smelter, where waste electrical and electronic equipment is co-processed with copper concentrate. Using the ecoinvent 3.10 cut-off system model, in which incoming scrap enters the inventory without upstream virgin burden, they report a footprint of approximately 2,000 kg CO_2 equivalent per kilogram of gold recovered. The dominant contributor is not energy supply but the fossil carbon content of the plastic fraction of the waste stream, which the authors show combusts during smelting and had been omitted from the underlying ecoinvent process in earlier work. Decarbonizing the electricity supply to the smelter, tested as a sensitivity scenario, produces only a modest reduction in the total, because the emissions are bound to the feedstock's own carbon content rather than to purchased energy.

Within the same paper, Fritz and Schmidt [4] collate a wider literature range that illustrates how far the reported figure moves once the allocation convention changes. High-value, selectively dismantled scrap, recovered without smelting, is reported at approximately 40 kg CO_2 equivalent per kilogram of gold. At the other extreme, a comparative study that does not apply cut-off treatment, so that copper scrap added to the smelter carries its upstream virgin burden forward, reports a pyrometallurgical result of 57,900 kg CO_2 equivalent per kilogram of gold, thirty times the cut-off figure for what is, in principle, a comparable process. A separate comparative study, when its results are re-expressed under economic allocation, which channels burden toward the highest-value output, yields figures between 10,000 and 400,000 kg CO_2 equivalent per kilogram of gold.

Table 1 sets these figures against the virgin-production benchmark reported by Nuss and Eckelman [5], whose cradle-to-gate life cycle assessment of sixty-three metals used economic allocation across co-product streams and identified gold and the platinum-group metals as carrying the highest reported burden per kilogram, a result the authors themselves attribute in part to the allocation method chosen rather than to the mining and refining chemistry alone.

Table 1: Reported carbon footprints for gold recovery from waste electrical and electronic equipment, by process route and allocation basis.

Reported Footprint (kg CO2e/kg Au)	Process Route	Allocation/Crediting Basis	Source
~40	Selective, high-grade dismantling scrap	Cut-off; clean feedstock, no virgin burden carried	[4]
~2,000	Pyrometallurgical smelting of WEEE co-processed with copper feed	Cut-off; feedstock combustion carbon from WEEE plastics included in inventory	[4]
5,840 (range 1,420-35,400 across routes)	Comparative pyro-, hydro-, electro- and biometallurgical PCB recovery	Not independently verified; full inventory not published in primary source	[4]
10,000-400,000	Comparative hydrometallurgical PCB-powder processes, re-expressed	Economic allocation, burden loaded onto highest-value output	[4]
17,900 hydrometallurgical, 57,900 pyrometallurgical, 1,230 novel routes	Comparative hydro-, pyro- and novel recovery routes	No cut-off applied; copper scrap carries upstream virgin burden	[4]
~30,000	Primary (virgin) production, cradle-to-gate	Economic allocation across co-product streams	[4,5]

The spread in Table 1 is not primarily a spread in chemistry. The 40 and 57,900 figures both describe recovery of gold from electronic scrap; the difference of nearly three orders of magnitude follows from whether the incoming material is treated as burden-free (cut-off) or as carrying forward the impact of the virgin material it once was (no cut-off), compounded by whether burden is apportioned by mass or by economic value. A regulator or purchaser presented with any single one of these numbers, without the accompanying allocation disclosure, cannot know where it sits within this range or why.

Case Study Two: Chromium Recovery from Industrial Wastewater

Muazu et al. [6] report a gate-to-gate life cycle assessment of hexavalent chromium removal from tannery and electroplating wastewater using a dual-chamber microbial fuel cell, in which chromium is reduced and precipitated at the cathode while bioelectricity is co-generated. The headline result is a global warming potential of negative 0.44 kg CO2 equivalent per kilogram of chromium recovered, a reported saving of up to 97% relative to conventional treatment technologies including ion exchange and chemical reduction-precipitation.

This result is produced by system boundary expansion. The authors explicitly credit the recovery system with three avoided burdens: displaced virgin chromium production, displaced grid electricity from the bioelectricity generated, and end-of-life recycling credits for the reactor's construction materials. The paper reports what happens when these allocated credits are withdrawn: the saving falls to 61.8%. It further reports the pre-credit process burden, dominated by the reactor's polymer casing and membrane materials, at positive 11 kg CO2 equivalent per kilogram of chromium recovered, a net-emitting result.

Table 2: Chromium recovery from industrial wastewater, reported result at each stage of avoided-burden accounting.

Accounting Stage	Reported Result	Basis	Source
Full avoided-burden accounting	-0.44 kg CO2e/kg Cr, up to 97% saving vs. conventional treatment	System boundary expanded to credit displaced virgin chromium, displaced grid electricity from bioelectricity generation, and end-of-life recycling of reactor materials	[6]
Allocated credits removed	61.8% saving retained	Same process inventory; avoided-burden credit streams withdrawn	[6]
Pre-credit process burden	+11 kg CO2e/kg Cr, net emitting	Reactor construction and operation burden alone, chiefly polymer cell encasing and membrane materials, before any avoided-burden allocation	[6]
Virgin ferrochrome comparator	3.3-10.3 kg CO2e/kg Cr	High-carbon ferrochrome production; industry-reported range spans a verified low near 3.3 to a global industry figure near 10	[7]

The comparator matters here as much as the accounting stage. Hamuyuni et al. [7] report high-carbon ferrochrome production at 3.3 to 10.3 kg CO2 equivalent per kilogram of chromium contained, consistent with the range separately reported by the ferrochrome industry. The pre-credit burden of the microbial fuel cell route, at 11 kg CO2 equivalent per kilogram, sits at or above the top of this virgin-production range. In other words, the claim that this recovery route is cleaner than virgin extraction holds only once the avoided-burden credit is applied; on a cut-off basis, charging the recovery system with its own construction and operating burden alone, the same process is not clearly cleaner than the material it would displace.

Boundary-Sensitivity Re-Analysis

The European Union's Circular Footprint Formula, documented by the Joint Research Centre for use under the Product Environmental Footprint method, formalizes the choice between cut-off and avoided-burden accounting as a single allocation factor, denoted A, bounded between 0.2 and 0.8. For a recycled-content product with recycled input share R1 and comparable material quality, the simplified formula reduces to a weighted average of the recycled-process impact and the virgin-production impact: the reported footprint equals A multiplied by the recycled-process impact, plus one minus A multiplied by the virgin impact. Setting A to one reproduces pure cut-off; setting A to zero reproduces pure avoided-burden.

Applying this formula to the gold case, using the Fritz and Schmidt [4] cut-off result of approximately 2,000 kg CO2 equivalent per kilogram and the Nuss and Eckelman [5] virgin benchmark of approximately 30,000, an allocation factor of 0.8, favoring the recycled-content credit, yields a reported footprint near 7,600; an allocation factor of 0.5 yields approximately 16,000; an allocation factor of 0.2, favoring virgin-production comparability, yields approximately 25,600. A single undisclosed choice of allocation factor is capable of moving the reported footprint of recycled gold from close to the virgin benchmark to less than a third of it, without any change in the underlying smelting process.

Applying the same logic to chromium, using the pre-credit burden of 11 and the virgin ferrochrome benchmark of 3.3 to 10.3 kg CO2 equivalent per kilogram, the Circular Footprint Formula produces results that remain close to or above the virgin range across most values of the allocation factor. Only the full avoided-burden convention used in the original study, equivalent to setting A to zero, produces the negative, strongly favorable result that has been reported as a 97% saving.

Displacement Assumption and Its Evidentiary Basis

Avoided-burden accounting rests on a further assumption that is independent of the allocation-factor question: that recovered material displaces virgin production on a one-to-one basis. The industrial ecology literature on displacement does not support this assumption for the metals where it has been empirically studied. Zink et al. [8] model displaced primary aluminum production in the United States and conclude that complete displacement is unlikely following a sustained increase in recycling supply, and that displacement approaching zero, or even negative displacement through market rebound, is possible. Ryter et al. [9] model the copper market using an economics-informed framework and report that a permanent increase in scrap supply displaces, on average, approximately half a kilotonne of mine production per kilotonne of additional scrap, with short-lived recycling policies displacing markedly less.

No comparable displacement study exists for gold or for chromium. The avoided-burden credit applied in both case studies above therefore rests on an assumption, complete displacement, that has not been tested for these specific markets and that the best-documented analogous markets contradict. Where the aluminum and copper evidence is taken as a guide, a chromium recovery route currently reported as achieving a 97% saving could see much of that credit withdrawn if displacement runs at the 50% to 68% central estimates reported for copper, or substantially more if it runs closer to the low, near-zero estimates modeled for aluminum under sustained supply increases.

Regulatory Context

The methodological choices examined above are not academic. The Battery Regulation requires carbon footprint declarations calculated under the Joint Research Centre's Product Environmental Footprint framework, which points toward the Circular Footprint Formula and its discretionary allocation factor, but the delegated and implementing acts specifying the precise calculation and verification rules had not been adopted as of mid-2026, and the associated compliance deadlines have been deferred pending their publication [1]. The Critical Raw Materials Act, in force since May 2024, empowers the European Commission to adopt delegated acts establishing environmental footprint calculation rules for specific critical raw materials, explicitly including greenhouse gas emissions as a required impact category, but the Commission's own prioritization report identifying which materials will be assessed first is not due until November 2026, and no per-material footprint rules for gold or chromium are yet in force [2].

Neither regulation currently fixes an allocation method for either metal examined in this paper. A carbon claim for secondary gold or chromium submitted into either framework today could legitimately be constructed under cut-off, avoided-burden, or any point along the Circular Footprint Formula's allocation-factor range, producing materially different, and in the gold case order-of-magnitude different, reported values, without violating any presently adopted rule.

A Minimum Disclosure Checklist

We propose that any carbon footprint claim submitted in support of secondary critical mineral recovery, whether for regulatory, procurement, or academic purposes, disclose four items. This is not a new standard; each item is already implied by the existing International Organization for Standardization framework for life cycle assessment and greenhouse gas quantification, and the checklist simply makes those requirements explicit and checkable for this specific product class.

First, the allocation method applied, stated as cut-off, avoided-burden, or Circular Footprint Formula with its allocation factor, following the allocation hierarchy set out in ISO 14044, which requires that the basis for allocation be defined and justified in advance of reporting results [3]. Second, the treatment of feedstock burden, stating explicitly whether the incoming waste or effluent stream is treated as burden-free or carries forward upstream impact, since this determination alone can account for an order of magnitude of difference in the gold case examined here. Third, the displacement assumption underlying any avoided-burden credit, stated as a rate rather than left implicit at 100%, consistent with the comparability requirements for functional units and system boundaries set out in ISO 14067 for product carbon footprints [10]. Fourth, the functional unit and system boundary, stated with sufficient precision, per kilogram of recovered metal against per unit of waste processed, cradle-to-gate against gate-to-gate, to allow independent recalculation.

This checklist is framed deliberately as a precondition for verifiability rather than as an additional standard. Under the assurance framework set out in ISO 14064-3 for the validation and verification of greenhouse gas assertions, a verifier cannot render an opinion on a secondary-recovery carbon claim without access to precisely these four items; their absence is not a stylistic omission but a barrier to independent assurance [11]. Prior harmonization efforts in the metals sector, notably Santero and Hendry [12], have aligned system boundaries and co-product allocation conventions for primary metal production; this work does not address disclosure requirements for the secondary-recovery, regulatory-facing carbon claim examined in this paper, which is the gap this checklist is intended to close.

4. LIMITATIONS

The two case studies were selected because each is drawn from published, peer-reviewed, gate-to-gate or cradle-to-gate life cycle inventory data with an explicitly stated allocation method, allowing the boundary-sensitivity re-analysis to be constructed from primary process data rather than from opaque secondary figures. The gold case draws part of its comparative literature range from studies compiled within a single peer-reviewed source; where the functional unit or allocation basis of an individual comparative figure was not independently verifiable from the original publication, this is noted in Table 1 rather than presented as confirmed. The chromium case is drawn from a single laboratory- and pilot-scale study; its absolute values carry the uncertainty inherent to early-stage technology, a limitation the original authors themselves quantify through operating-parameter sensitivity analysis, though this uncertainty does not affect the paper's central finding regarding the sensitivity of the reported result to the allocation and crediting method chosen.

The direction of the boundary artifact identified here is not uniform. Cut-off accounting, common in cradle-to-gate reporting and in environmental product declarations, tends to understate the credit due to recovery routes by denying them any displacement benefit while still charging feedstock-embedded burden; avoided-burden accounting tends to overstate that credit by assuming complete displacement. The appropriate conclusion is not that either convention is invalid, both are permitted under ISO 14044, but that a comparison constructed under one convention is not informative about performance under the other, and that regulatory or procurement decisions built on an undisclosed convention rest on a choice the decision-maker cannot see.

5. CONCLUSIONS

For the two recovery routes examined here, the reported carbon advantage of secondary critical mineral recovery over virgin extraction is substantially a function of system-boundary and allocation choices that are rarely disclosed alongside the headline figure, and that current regulatory frameworks have not yet fixed for either metal.

A minimum disclosure checklist, comprising allocation method, feedstock burden treatment, displacement assumption, and functional unit, would not resolve the underlying methodological choice, which remains legitimately contested, but would make the choice visible, and in doing so allow carbon claims for secondary critical mineral recovery to be compared, verified, and relied upon with the same rigor already required of the underlying life cycle assessment standards.

REFERENCES

1. European Parliament, Council of the European Union. Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC (Text with EEA relevance). 2023. Available from: http://data.europa.eu/eli/reg/2023/1542/2025-07-31
2. European Parliament, Council of the European Union. Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020 (Text with EEA relevance). 2024. Available from: http://data.europa.eu/eli/reg/2024/1252/2024-05-03
3. International Organization for Standardization. ISO 14044:2006. Environmental management—Life cycle assessment—Requirements and guidelines. Geneva (CH): ISO; 2006.
4. Fritz B, Schmidt M. Climate change vs. circular economy: challenges of the most common route for recycling gold from WEEE. Sustainability. 2025; 17:2086. doi:10.3390/su17052086.
5. Nuss P, Eckelman MJ. Life cycle assessment of metals: a scientific synthesis. PLoS One. 2014;9: e101298. doi: 10.1371/journal.pone.0101298.
6. Muazu RI, Sadhukhan J, Venkata Mohan S, Gadkari S. Hexavalent chromium waste removal via bioelectrochemical systems: a life cycle assessment perspective. Environ Sci Water Res Technol. 2023; 9:2487-2500. doi:10.1039/D3EW00344B.
7. Hamuyuni J, Johto H, Haimi E, Bunjaku T, Mäkelä E, Lindgren M. Energy consumption and greenhouse gas emissions of high-carbon ferrochrome production. JOM. 2023; 75:3512-3522. doi:10.1007/s11837-023-05707-8.
8. Zink T, Geyer R, Startz R. Toward estimating displaced primary production from recycling: a case study of U.S. aluminum. J Ind Ecol. 2018;22(2):314-326. doi:10.1111/jiec.12557.
9. Ryter J, Fu X, Bhuwalka K, Roth R, Olivetti E. Assessing recycling, displacement, and environmental impacts using an economics-informed material system model. J Ind Ecol. 2022;26(3):1010-1024. doi:10.1111/jiec.13239.
10. International Organization for Standardization. ISO 14067:2018. Greenhouse gases—Carbon footprint of

products—Requirements and guidelines for quantification. Geneva (CH): ISO; 2018.

11. International Organization for Standardization. ISO 14064-3:2019. Greenhouse gases—Part 3: Specification with guidance for the verification and validation of greenhouse gas statements. Geneva (CH): ISO; 2019.
12. Santero N, Hendry J. Harmonization of LCA methodologies for the metal and mining industry. Int J Life Cycle Assess. 2016;21(11):1543-1553. doi:10.1007/s11367-015-1022-4.

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