



Perspective

The energy transition paradox: how declining ore grades are undermining the sustainability of primary metal extraction

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ARTICLE INFO

Keywords:

Ore grade

Mining

Recycling

Lithium-ion battery

Carbon footprint

The global energy landscape is undergoing a transformation towards renewables. In 2024, clean energy sources—including renewables and nuclear—reached over 40 % of the global electricity supply, with solar energy being the fastest-growing source for two decades. Energy transition is expected to reduce the environmental burden of energy-intensive sectors by decreasing the carbon intensity of electricity supply and eliminating fossil fuel conversion losses. However, despite grid decarbonization benefiting all energy-intensive sectors, the net advantage for mining and processing primary raw materials may be offset by declining ore grades and the need to access deeper or less accessible deposits, which increase the carbon footprint of extraction.

This potential trade-off also emerges from the contrasting expectations reported by prospective studies on the carbon footprint of primary metal production per kilogram of metal. According to Harpprecht et al. (2024), views on future trends in the literature diverge and heavily depend on the influencing variables and the scenarios analyzed, which are usually unstandardized in assumptions and description. Moreover, the literature is limited in scope: only 15 metals have been examined, and just six of them (Cu, Fe, Al, Ni, Zn, and Pb) in more than two studies, leaving several key metals for the energy transition largely overlooked.

The decline in ore grades is well documented for several metals, such as copper and gold. As high-grade deposits are exhausted, mining operations are increasingly turning to lower-grade ores, often located in remote or geologically complex areas. This leads to a sharp decline in energy efficiency and a corresponding increase in emissions due to a sublinear relationship between material abundance and production

rates (Zanoletti et al., 2024).

In contrast, secondary raw materials - especially those accessed through urban mining and recycling - contain higher metal concentrations than primary ores. As recycling processes become increasingly powered by renewable electricity, their sustainability is expected to further improve, making them environmentally and energetically preferable material sources.

Determining whether primary or secondary extraction is more sustainable is not straightforward and depends on multiple variables: ore grade, energy mix, infrastructure, process efficiency, and regulations. In some cases, secondary production has clearly lower emissions; in others, various constraints may favour primary sources. However, datasets linking ore grade decline to energy and emission intensity to support comparisons between primary and secondary production are limited. Most available studies rely on simulations rather than real-world data, and cross-material or cross-regional comparisons are rare. The picture is further complicated by differences in mining operations: underground mines typically consume more energy than open-pit ones due to hoisting, ventilation, and other energy-intensive needs.

Evaluating the variations in carbon footprint of primary production over time allows understanding the impact of cumulated production on environmental sustainability. As an example, Fig. 1 presents carbon footprint (CF) variations for primary production of some critical metals between 2019 and 2024, plotted against the corresponding changes in global production.

It must be acknowledged that, despite originating from reliable

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<https://doi.org/10.1016/j.resconrec.2025.108658>

Received 6 August 2025; Received in revised form 26 September 2025; Accepted 21 October 2025

Available online 27 October 2025

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sources, the data plotted in Fig. 1 may be affected by limitations. First, data may exhibit temporal inconsistencies: although they were extracted from the 2019 and 2024 versions of the databases, the underlying values may refer to different original time periods. As a result, in some cases the reported % variation corresponds to an actual timespan longer than five years. Second, data about carbon footprint may not capture the full range of sources, geographical locations of extraction (and associated ore grades), or processing routes, and therefore may have limited representativeness of the actual global CF average. These shortcomings, however, are common across the literature. Thus, while they call for caution in interpreting the reported numbers too literally, such data allow for broader reflections and general insights. In the light of this premise, Fig. 1 reveals various trends. Some industrial elements, such as chromium, sulphur, aluminium, and tin, show stable or even reduced CF *per kg* despite production growth, indicating increased process efficiency or resource accessibility. Precious metals such as silver, gold, and platinum show dramatic increases in CF (about 350 %, 140 %, and 180 %, respectively), with relatively modest changes in production. This suggests a worsening extraction efficiency, likely due to deeper or lower-grade deposits being exploited. Lithium and cobalt, the main metals in batteries, stand out as the most deviating in terms of CF variation. Cobalt exhibits the highest increase in CF—over 400 %—with a 100 % increase in global production. This suggests a significant deterioration in extraction efficiency, most likely driven by a sharp decline in ore grades. Lower-grade ores require more energy for extraction and processing, which in turn leads to a disproportionately higher environmental burden per unit of metal produced. In the case of lithium, the data reveal a great increase in production (over +200 %) and CF (over +300 %), positioning it as another outlier in the upper-right quadrant of the plot. Currently, lithium is mainly produced (around 55 %) through the spodumene route, primarily from ores mined in Australia. In contrast, South American countries contribute about 35 % of the global supply via brine-based extraction. More recently, China has introduced a third route, relying on domestic lepidolite deposits. The observed changes in lithium's carbon footprint may therefore be associated with evolving strategies in resource sourcing.

Recovering critical materials from end-of-life products or industrial residues reduces environmental impacts and diversifies supply chains. Importantly, as ore grades decline and clean energy becomes more accessible, some low-grade ores or tailings classified as “waste” may

become economically and environmentally viable through advances in processing and energy use optimization. Technology and clean electricity may redefine the boundary between “ore” and “waste”, unlocking new sustainable resource streams. In recycling, particularly in battery treatment, the impact of energy mix changes is expected to be more evident in technologies using thermal steps, where CF is highly sensitive to electricity sources. Mechanical processes may be less affected, and chemical inputs (e.g., reagents) remain largely independent of the energy mix.

However, the untapped potential of recycling and circular economy strategies is still underestimated, with the greatest attention by political authorities turned towards securing primary resources, thus generating geopolitical tensions. Urgent systemic changes are therefore needed. Cleaner electricity alone is not sufficient to reduce the environmental costs of metal extraction. A shift toward secondary sources—especially in the case of lithium-ion batteries, where multiple metals can be recovered—can significantly reduce the carbon footprint of raw material supply.

This evidence highlights that the sustainability of primary metal production must be assessed both from an environmental perspective and in terms of resource security. In the current context of geopolitical tensions and supply risks, the paradox of the energy transition becomes evident: while electricity grids are decarbonizing, the environmental burden of raw material extraction continues to rise. Addressing this contradiction requires urgent and coordinated action by industry and policymakers alike to ensure that the energy transition remains truly sustainable.

Future research should adopt an integrated and material-crossing perspective, including multi-metal recovery systems and regionalized life cycle assessments. Such assessments should rely on data as comprehensive and reliable as possible, reflecting the actual distribution of geographical sources of material extraction and processing routes. In addition, they should ensure temporal consistency to enable a robust evaluation of trends in CF (or energy intensity) content, allow for comparisons, and support generalizations. They should also incorporate economic analyses to assess cost-effectiveness and investment viability for primary vs. secondary supply chains. Only by addressing both the energy and material dimensions of the transition can we ensure that decarbonization does not come at the expense of other environmental objectives.

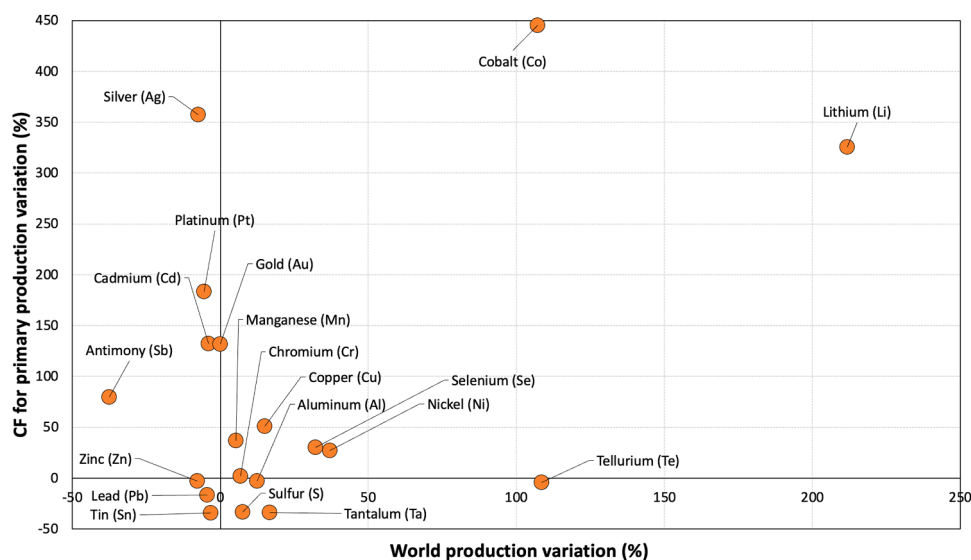


Fig. 1. Percentage change between 2019 and 2024 in carbon footprint (CF) for primary element production per unit—e.g., expressed in $\text{kgCO}_2\text{eq/kg}$ —versus global production variation in the same period. Data on global material production are obtained from the Mineral Commodity Summaries published by the U.S. Geological Survey. Data on CF are extracted from Ansys Granta Selector (previously CES Selector) MaterialUniverse and Eco databases, which rely on the Ecoinvent database and other scientific sources.

CRediT authorship contribution statement

Elza Bontempi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Nicola Saccani:** Writing – review & editing, Writing – original draft, Methodology.

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

This study was carried out within the MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO

1.3 – D.D. 1551.11-10-2022, PE00000004). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Data availability

Data will be made available on request.

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