DTU Library

# Assessing the social and environmental impacts of critical mineral supply chains for the energy transition in Europe

**Berthet, Etienne; Lavalley, Julien; Anquetil-Deck, Candy; Ballesteros, Fernanda; Stadler, Konstantin; Soytas, Ugur; Hauschild, Michael; Laurent, Alexis**

*Published in:*
Global Environmental Change

*Link to article, DOI:*
10.1016/j.gloenvcha.2024.102841

*Publication date:*
2024

*Document Version*
Publisher's PDF, also known as Version of record

Global Environmental Change 86 (2024) 102841

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

# Assessing the social and environmental impacts of critical mineral supply chains for the energy transition in Europe

Etienne Berthet [a,b,1,*], Julien Lavalley [a], Candy Anquetil-Deck [c], Fernanda Ballesteros [d], Konstantin Stadler [c], Ugur Soytas [e], Michael Hauschild [a,b], Alexis Laurent [a,b]

[a] Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark (DTU), Kgs. Lyngby, Denmark

[b] Center for Absolute Sustainability, Technical University of Denmark (DTU), Kgs. Lyngby, Denmark

[c] Industrial Ecology Digital Laboratory, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

[d] German Institute for Economic Research (DIW), Berlin, Germany

[e] Climate Economics and Risk Management, department of Technology, Management and Economics, Technical University of Denmark (DTU), Kgs. Lyngby, Denmark

ARTICLE INFO

*Keywords:*
Modern slavery
Mining
Energy transition
European Green Deal
Critical minerals
Decarbonization divide

ABSTRACT

Advanced technologies are inherently dependent on critical minerals and their related metals. The mining extraction of these critical minerals leads to significant social and environmental impacts that extend beyond the regions where those advanced technologies are ultimately used. This study explores the global socio-environmental challenges arising from the European Climate Law's aim for net-zero greenhouse emissions by 2050, focusing on the EU's consumption of critical minerals. Developing a novel methodology based on Multi-Regional Input-Output (MRIO) model, enriched with detailed mineral production data from specific ore-to-mineral ratios and socio-environmental information, this work assesses the impacts of the EU's mineral consumption within its energy transition framework. This innovative approach extends beyond ore extraction to encompass all stages of the supply chain. Key findings indicate that the continental Europe accounts for 60% of the EU's ore extraction footprint, yet only 35% of the mineral footprint for the 34 analyzed critical minerals. In contrast, Africa's and South America's shares are 12% and 29%, respectively, markedly higher than attributed in previous studies. The study highlights challenges in securing these minerals, including potential usage conflicts and increased mining in water-scarce basins within Australia, Kazakhstan, South Africa, and Chile, hence exacerbating environmental and community issues. Furthermore, the research suggests that achieving the EU's climate goals could expose between 15 and 89,000 African miners to increased modern slavery vulnerabilities by 2040. However, adherence to the EU Green Deal principles could mitigate these risks and recommendations are proposed, including diversifying mineral supply chains, establishing partnerships with countries that maintain high socio-environmental standards, and adopting circular economy paradigms and innovative solutions. This study advocates its new methodological development to build comprehensive strategies balancing climate goals with the global socio-environmental effects of critical mineral extraction, especially in developing countries.

## 1. Introduction

The European Climate Law, adopted in 2021, cemented the EU's ambitious pledge to achieve net-zero greenhouse gas (GHG) emissions by 2050, establishing an interim target to reduce emissions by 55 % below 1990 levels by 2030. These objectives, framed within the "Fit for 55" package, foresee a significant increase in renewable energy production and the implementation of "clean energy technologies" such as nuclear energy, electricity networks, electric vehicles, battery storage, and hydrogen production and storage (European Commission, 2019; European Commission, 2021a; European Commission, 2021b). The availability of specific mineral resources – such as cobalt, lithium, nickel, copper, and rare-earth elements – emerges as a critical determinant for a successful energy transition. Both the International Energy

* Corresponding author at: Technical University of Denmark (DTU), Bygningstorvet 115, Office 065, 2800 Kgs. Lyngby, Denmark.
*E-mail address:* etber@dtu.dk (E. Berthet).

[1] Present contact address: Yale Center for Environmental Law and Policy, Yale University, Kroon Hall, G31, 195 Prospect St, New Haven, CT 06511 USA, etienne.berthet@yale.edu.

https://doi.org/10.1016/j.gloenvcha.2024.102841
Received 11 September 2023; Received in revised form 3 February 2024; Accepted 28 March 2024
Available online 10 April 2024

Agency (IEA) and the International Renewable Energy Agency (IRENA) have underscored the centrality of those critical mineral resources in their recent publications (Gielen, 2021; IEA, 2021a, 2021b; IRENA, 2021).

The extraction and processing of critical minerals generate significant global impacts, accounting for 10 % of GHG emissions in 2018 – a proportion expected to rise due to increasing demand and dwindling ore quality (Azadi et al., 2020). In addition, the localized repercussions of these extraction activities are equally concerning. Among the local environmental impacts, chemical pollution, including water and soil contamination, poses significant environmental challenges (Balaram, 2019; Jiang et al., 2020; Marx et al., 2018). On the social front, mining activities present a complex picture. On the positive side, they can catalyze job creation and economic growth, offering an escape from poverty (Mancini and Sala, 2018; Sovacool, 2019). Mining contributes to community development, enhances social and cultural identity (Sovacool, 2019), and promotes infrastructure improvements, including in telecommunications and utilities (Azapagic, 2004; Franks, 2012; Hajkowicz et al., 2011). However, particularly in developing countries, the industry is plagued by significant drawbacks such as corruption, child and forced labor, poor working conditions, low wages, and health risks, often in violation of the International Labour Organization (ILO) conventions (Azapagic, 2004; Environmental Law Alliance Worldwide (ELAW), 2010; Franks, 2012; Hajkowicz et al., 2011; Mwaura, 2019; Sovacool, 2019; Spohr, 2016; Starke, 2016).

Critical minerals are primarily extracted from a select few countries (IEA, 2021a), thereby concentrating the localized impacts within these regions. Furthermore, these extraction activities often serve as the starting points for extensive global supply chains. The result is localized impacts that are often geographically distant from where the minerals are finally utilized. This spatial disconnection creates a "decarbonization divide" (Sovacool et al., 2020), whereby developed countries reap the benefits of cleaner technologies while developing and least-developed countries often bear the environmental and social burdens. This divide not only complicates future decarbonization initiatives in those developing countries but also exacerbates existing inequalities (Sovacool et al., 2020).

The importance of critical minerals for the EU has already been extensively studied (e.g., (Blengini et al., 2017; Černý et al., 2021; Ciacci et al., 2020; European Commission, 2014; Hetherington and Bloodworth, 2010; Hofmann et al., 2018; Løvik et al., 2018; Mancini et al., 2018). Initiatives such as the European Raw Materials Alliance (ERMA) have emerged to fortify the EU's resilience to supply chains disruptions. Most of those initiatives consider the problem through the lens of strategic supply issues and material criticality (Eurometaux, 2019; European Commission, 2020). Furthermore, while a subset of the academic literature has delved into the environmental and societal implications of extracting and processing critical minerals (Chaves et al., 2021; Jiang et al., 2020; Liu et al., 2019; Liu and Agusdinata, 2020), the primary lens remains production-centric, emphasizing the impacts of an increase in the production of those minerals. However, Sovacool et al. (2020) have underscored the need to incorporate upstream factors in the mineral consumption supply chain to fully understand the "decarbonization divide". This shift away from a solely production-centric view to the measure of local impacts for a specific consumption (or consumption perspective) necessitates methodological advancements (Markkanen and Anger-Kraavi, 2019). This is imperative for crafting equitable global environmental policies leading to a just and sustainable global transition (Sovacool et al., 2020).

Considering these challenges, two pressing inquiries emerge: Firstly, how might we craft a methodology that encapsulates the global social and environmental repercussions stemming from a specific use – in this study's context, the implications of critical mineral extraction driven solely by the EU's energy transition demands? Secondly, can this methodology be broadened to aid in formulating inherently more sustainable policies, thereby curtailing indirect adverse environmental and societal ramifications?

In addressing the abovementioned queries, this article introduces a novel methodological approach. We utilize a consumption-based approach built upon diverse Multi-Regional Input-Output (MRIO) frameworks (Leontief, 1970). MRIO models, with their capacity to trace supply chains to their ultimate demand, irrespective of their internationalization and decentralization, serve as an ideal scaffold for our investigation. However, a notable limitation of these models is their lack of detailed data on ore extraction, mineral transformation, and metal production. This gap is particularly evident when attempting to accurately assess the footprints of specific end-uses, such as the energy transition, detailed at the metal level. Most existing material footprint research focuses on ore extraction at national or regional levels, providing limited insights into the impacts at the mineral or metal level (Wiebe et al., 2018; Wiedmann et al., 2015;). Furthermore, studies that do examine specific end-uses, such as those on electric vehicles (Sen et al., 2019), tend to remain at a broader sectoral level. A methodological advancement has been the integration of MRIO data with Material Flow Analysis (MFA) data (Giljum et al., 2016) on this topic, though this approach is not without challenges. It notably struggles with ores comprising multiple metals, where MFA databases often attribute the total ore volume to the economically dominant metal, relegating others to by-product status (Giljum et al., 2016, Additional file 3: Technical details on the compilation of the global material flow database, 2016) and thus without integrating them into the footprint. Additionally, the different MRIO models present scarcity and large uncertainty for data related to workforce and working conditions (Stadler et al., 2018, SI7,) and do not currently integrate detailed social effects, such as child labour or forced labour (or what is broadly categorized as modern slavery).

Our proposed methodological approach endeavours to bridge these gaps via two main contributions. First, we augment two distinct well-established MRIOs - Eora (Lenzen et al., 2013) and EXIOBASE (Stadler et al., 2018) - by incorporating comprehensive mineral production data. This integration utilizes a novel method based on varying ore-to-mineral ratios, allowing us to estimate the quantity of ore required to produce a unit of mineral. Second, we also fully integrate the latest available data about workforce and working conditions in these models to calculate the social impacts of the related supply chains.

In addition to the methodological contributions, this study provides quantitative indicators to assist national and international policymakers in selecting supply chains with the lowest environmental and social impacts and/or enhancing the efficiency of their mitigation effects. By developing a more holistic approach to critical minerals extraction and processing, this study creates insight to support a socially fair and environmentally sustainable energy transition.

The paper is structured to first present a methodological approach for calculating national mineral footprints and incorporating modern slavery data in Section 2. Section 3 harnesses these methodologies to devise scenarios explicitly crafted to encapsulate the EU's energy transition, contextualized within the ambit of the European Green Deal. The main findings are presented in Section 4, while Section 5 offers quantitative metrics and suggestions to address gaps in current European policies, aiming to mitigate negative environmental and social impacts.

## 2. Material and methods

### 2.1. The multi-regional input-output (MRIO) framework

The MRIO framework (Leontief, 1970) is crucial for tracing the externalities generated from the production of commodities to their consumption (Miller and Blair, 2009; Wiedmann, 2009). This framework is well-suited for our approach as it accounts for supply chains and their end demand, irrespective of how international or decentralized they are. By integrating various environmental databases, MRIO models also capture a range of environmental impacts. These augmented MRIO models have been key in calculating various types of footprints such as water, material, carbon, and land, and have been applied in the evaluation of household, national, and global consumption patterns (Ivanova et al., 2016; Tukker et al., 2016; Wiedmann et al., 2015).

The study employs two specific MRIO models, Eora (Lenzen et al., 2013) and EXIOBASE (Stadler et al., 2018), which have been enhanced with detailed data on mineral production and the requirements for energy transitions. This allows for an accurate calculation of the mineral footprint associated with the EU's shift in energy policy.

### *2.2. Overview of the EU ore and mineral footprints for clean energy technologies*

The ore footprints of clean energy technologies deployed within the EU were computed using the selected MRIO models. We adopted a consumption-based approach to calculate the quantity of ore extracted, the fraction subsequently converted into minerals, and the amount that ultimately meets the EU's demand, specifically triggered by clean energy technologies. The technological purview, as delineated by IEA (2021a), encompasses renewable power sources such as solar photovoltaic, onshore and offshore wind, concentrating solar power, hydro, geothermal, and biomass, along with nuclear power, electricity networks, electric vehicles, battery storage, and hydrogen technologies. These technologies necessitate metals and alloys derived from mineral-containing ores. Within the framework of this research, we define distinct footprint types.

The "*ore footprint*", which is the quantity of ore globally extracted to supply the demand of one specific pair country(ies)/sector(s). This is the footprint traditionally calculated in the literature for EU critical mineral analyses. Subsequent to ore extraction, the next phase involves releasing and concentrating the desired minerals from the ores, accomplished through grinding and selective mineral separation. Here the "*mineral footprint*" quantifies the volume of ore(s) needed to produce a given quantity of mineral(s). A comprehensive supply chain analysis would further necessitate the calculation of metallurgical and alloys footprints. However, such measurements were not needed for this study as the selected energy system development scenarios indicate the requirements for the EU clean energy transition in terms of minerals and not in terms of metals or alloys (IEA, 2021a). Finally, we focus on the quantity of mineral that is finally used to supply the demand of one specific pair country(ies)/sector(s). Consequently, the "*mineral footprint for clean energy transition*" refers exclusively to the segment of the mineral footprint fulfilling the energy transition-induced demand. This tailored footprint enables a precise assessment of ore extraction and its subsequent conversion into specific minerals. Our study encompasses the entire mineral value chain from extraction to processing. For consistency with the IEA (2021a) report, mineral nomenclatures were harmonized with their respective metal transformations. As an illustrative instance, the term "*titanium mineral footprint*" represents the quantity of ore extracted (titanium-iron ore, i.e. ilmenite), then transformed into a mineral (titanium oxide), then transformed into a metal (titanium) and transformed into an alloy (titanium mixed with other chemical elements). The EU mineral footprint for clean energy transition detailed above is illustrated Fig. 1.

As previously mentioned, the switch from the ore footprint to the mineral footprint has remained a challenge in past MRIO models as their broad sector may covers a type of ore from which several minerals can be extracted. To solve this issue, our study introduces a novel approach for integrating detailed mineral production data into MRIO, utilizing specific ore-to-mineral ratios to precisely estimate the required quantity

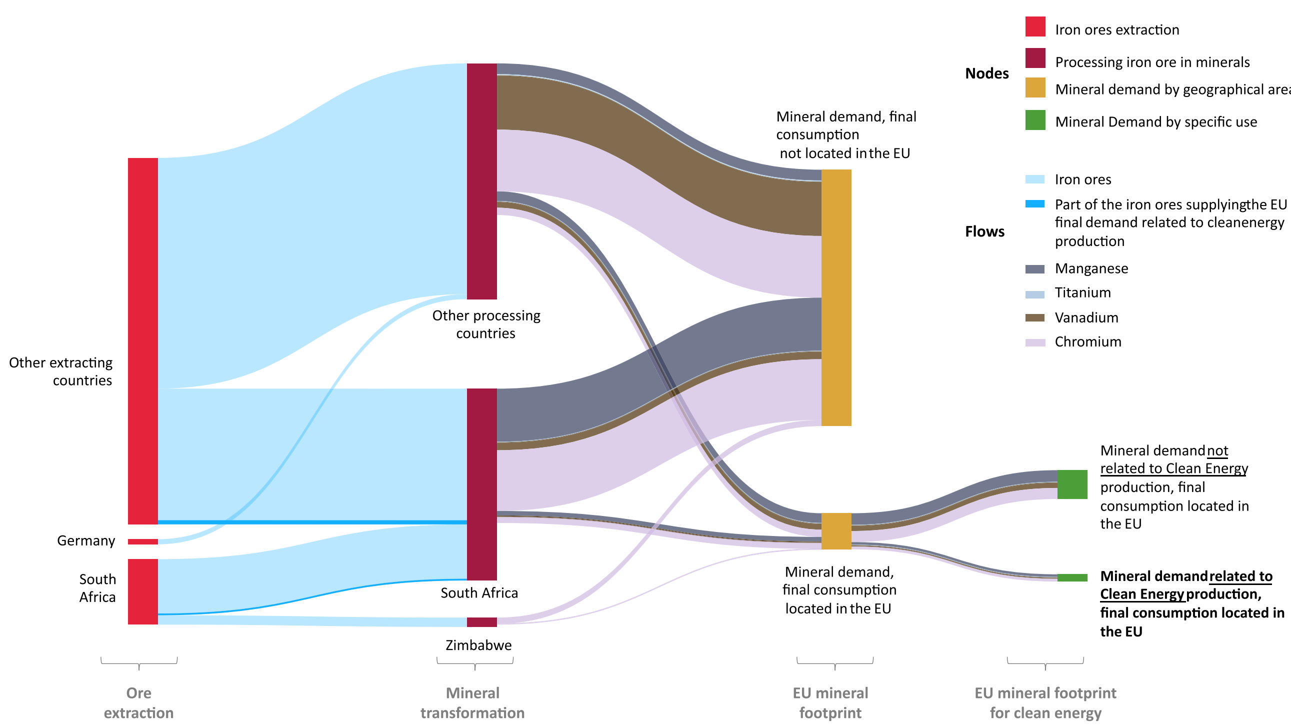



**Fig. 1.** This graphic showcases the ore and mineral footprints for some minerals essential for the EU's clean energy technologies. Using iron ore as a simplified representative flow, it highlights critical minerals derived from it, such as the oxides of manganese, titanium, vanadium, and chromium. The visualization excludes non-critical minerals from iron ores. Germany, South Africa, and Zimbabwe are spotlighted, each reflecting unique ore and mineral production profiles: Germany: Engages in ore extraction without mineral transformation, South Africa: Undertakes both ore extraction and transformation, and also imports ores for mineral processing, Zimbabwe: Primarily transforms imported ores without local extraction. The illustration progresses from detailing ore extraction to showcasing EU's specific mineral demands for clean energy technologies, ending with a dark blue representation of the EU's ore footprint for these technologies. Though flow proportions are correct, only 10% of various flows are visually represented for clarity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of ore for producing each unit of mineral. Although previous studies, such as Giljum et al. (2016), have applied this technique to specific ore-mineral pairs, like lead and zinc, the distinct novelty of our work lies in its comprehensive application as we extend this approach across the entire spectrum of minerals and metals required for a given end-use. The scope of the different minerals as well as the different ratios are summarized in Table 1 (see also SI_S1 1.6 and SI_S2 for the fully detailed results).

### 2.3. Inclusion of the social impacts

In the field of sustainability, Social Life Cycle Assessment (SLCA) has emerged as a valuable tool to assess the social and economic impacts associated with geographic locations and stakeholder categories along the life cycle of products. Despite its widespread application and methodological guidelines established in 2009 (Benoît et al., 2010) the methodology is still in its early stage (Mancini and Sala, 2018). One of the main challenges in combining MRIO and SLCA approaches is the

**Table 1**
This table delineates the two primary approaches used for disaggregating ore categories in our study. For minerals with available USGS data, "Gross Weight from USGS" was directly applied. In contrast, for minerals lacking USGS data, we estimated ore grade ratios based on extensive literature review, enabling calculation of ore gross weight from mineral extraction data. Detailed methodologies and source references are available in Supplementary Information Sections SI 1.6–1.8 and SI 2.

| Material | Ore | EXIOBASE ore category | Eora ore category | Main source production | Method for ore desegregation | Ore desegregation value | Comments and sources |
|---|---|---|---|---|---|---|---|
| Gallium | Bauxite and Aluminium ores | Bauxite and aluminium ores | Bauxite and other aluminium ores | World Mining Data (WMD) | Ore grade ratio | 0.00005 | Most of the global gallium supply is obtained as a by-product of aluminium mining from bauxite ores (Lu et al., 2017) |
| Copper | Copper ores | Copper ores | Copper ores | WMD | Ore grade ratio | 0.05 | (Basov, 2017) |
| Selenium | | | | WMD | Ore grade ratio | 0.00005 | Selenium and tellurium are mostly recovered as by-products of copper mining (Bleiwas, 2010). Source ore grade ratio selenium: Wang (2016). Source ore grade ratio tellurium: Goldfarb (2015) |
| Tellurium | | | | WMD | Ore grade ratio | 0.00002 | |
| Cobalt | | | | WMD | Ore grade ratio | 0.002 | Cobalt is obtained as a by-product of copper or nickel ore mining (depending on the extraction place) (Dehaine et al., 2021) |
| | Nickel ores | Nickel ores | Nickel ores | WMD | Ore grade ratio | 0.0007 | |
| Nickel | | | | WMD | Ore grade ratio | 0.02 | (Surianti et al., 2020) |
| Chromium | Chromium ores | Iron ores | Iron ores | WMD | Gross weight from USGS | | Chromium, manganese, titanium, and vanadium are mostly extracted from ferrous ores (Koleli and Demir, 2016; Yang et al., 2021) |
| Manganese | Manganese ores | | | WMD | | | |
| Titanium | Titanium ores | | | WMD | | | |
| Vanadium | Vanadium ores | | | USGS | Ore grade ratio | 0.015 | (Moskalyk and Alfantazi, 2003) |
| Lithium | Lithium ores | Other non-ferrous metal ores | Other metal ores | WMD | Gross weight from USGS | | |
| Molybdenum | Molybdenum ores | | | WMD | Ore grade ratio | 0.4 | (Van den Berg et al., 2002) |
| Niobium | Niobium ores | | | WMD | Ore grade ratio | 0.35 | (Deblonde et al., 2016) |
| Tantalum | Tantalum ores | | | WMD | Ore grade ratio | 0.42 | |
| Tungsten | Tungsten ores | | | WMD | Ore grade ratio | 0.01 | (Han et al., 2021) |
| Hafnium | Zircon ores | | | Critical Raw Material (CRM) Alliance | N/A | N/A | World production data in extremely limited quantity (less than 100 tons annually) (Critical Raw Materials Alliance) |
| Zirconium | | | | WMD | Extraction ratio | 0.8 | (Reichl and Schatz, 2021) |
| Dysprosium | REOs ores | | | USGS | Extraction ratio | 0.0089 | (National Minerals Information Center, 2023) |
| Neodymium | | | | | Extraction ratio | 0.16 | |
| Praseodymium | | | | | Extraction ratio | 0.047 | |
| Terbium | | | | | Extraction ratio | 0.0018 | |
| Iridium | Platinum Group Metal ores | PGM ores | Gold, silver, platinum, and other precious metal ores | USGS | The ratio is estimated by a weighted average of iridium, platinum, and silver (Eora only) ratios with their respective mineral production weight | | |
| Platinum | | | | WMD | | | |
| Silver | Silver ores | Silver ores | | WMD | N/A | N/A | |
| Tin | Tin ores | Tin ores | Tin ores | WMD | N/A | N/A | |
| Lead | Lead ores | Lead ores | Lead ores | WMD | N/A | N/A | |
| Cadmium | Zinc ores | Zinc ores | Zinc ores | WMD | Ore grade ratio | 0.004 | Cadmium, germanium, and indium are mostly recovered as by-products of zinc mining (Bleiwas, 2010). Cadmium source: Sadegh Safarzadeh et al., (2007). Germanium source: Ruiz et al., (2018). Indium source: Watari et al., (2020) |
| Germanium | Zinc ores | | | WMD | Ore grade ratio | 0.0036 | |
| Indium | Zinc ores | | | WMD | Ore grade ratio | 0.00032 | |
| Zinc | Zinc ores | | | WMD | Ore grade ratio | 0.1 | (Calvo et al., 2016) |
| Boron (Boron trioxide) | Boron ores | Other minerals | Other mining and quarrying products | WMD | Extraction ratio | 0.6 | (Reichl and Schatz, 2021) |
| Graphite (Crystalline flake graphite) | Graphite ores | | Quarrying of sand and clay | USGS | Ore grade (crystalline flake) | 0.17 | (Jara et al., 2019) |
| Magnesium | Magnesite ores | | | USGS | Directly Available in WMD | | |
| Silicon | Silicon ores | Gravel and sand | | USGS | Gross weight from USGS | | |

accuracy of social satellite data, particularly regarding employment data. To address this issue, we update/create them for both MRIO models used in our study before applying ratios of quantity of ore extracted for clean energy technologies in the EU (see Section 3.3, Equation (8). For more information about the update of employment data cf. SI_S1 1.11.

Another challenge in assessing social risks is selecting an appropriate framework. Assessing social risks in mining, especially in developing countries with Artisanal Small-scale Mining (ASM), is challenging due to limited official information on social issues faced by workers. The study by Sovacool (2021) on ASM in the Democratic Republic of the Congo (DRC) uses a framework of "modern slavery", "dispossession", and "gendering" to analyze these issues. These elements are interconnected: gendering induces labor inequality and societal gender norms, leading to dispossession, which often affects women more and is linked to poverty and violence. Modern slavery, a form of coercion, is primarily a result of labor inequality and results in key social issues like violent exploitation, patriarchy and prostitution effects, and child labor. While all these different elements could help us to identify social risks in mining and supply chains, our analysis focuses only on the modern slavery aspect. This choice is mainly motivated by (i) the predominance of this social risk over others within the mining sector (Mancini et al., 2018) (ii) the large associated social and external costs of modern slavery throughout the international supply chains (Gold et al., 2015), even though firms' capabilities to mitigate this risk have been limited in extended supply chains (Geng et al., 2022), with ambiguity leading to policy resistance (Meehan and Pinnington, 2021); (iii) the intricate reinforcing mechanisms between modern slavery and environmental damage and climate change (Bales and Sovacool, 2021); and (iv) the relatively complete and well-documented data pertaining to modern slavery that are comparable across most countries. Hence, the authors reviewed main SLCA databases, the Social Hotspot Database (SHDB) and the Product Social Impact Life Cycle Assessment (PSILCA) - as they both deal with modern slavery - to gather accurate information from literature.

The SHDB was initially developed in 2009 to measure supply chain human rights and working conditions (Norris and Norris, 2015; Norris et al., 2013) and the PSILCA was inspired directly by UNEP/SETAC guidance (United Nations Environment Programme, 2009). Both databases use the Global Slavery Index (GSI) for information related to forced labor prevalence. Nonetheless, our analysis suggested a stronger inclination towards the GSI's vulnerability model. This model seeks to elucidate factors contributing to or predicting the incidence of modern slavery. Thus, nations with minimal actual modern slavery cases can still register high risk due to factors like poverty, economic disparity, or political turmoil which can elevate vulnerability to slavery. For an in-depth integration methodology of the GSI vulnerability model, readers are directed to SI_S1 1.12.

## 3. Calculation

### 3.1. Calculating the EU mineral footprint

The first step is to determine the EU mineral footprint. However, it is currently not possible to calculate this mineral footprint directly as it requires MRIO satellite and stressors data about mineral production weight, which are not available for any MRIO. The relationship between ores and minerals is a helpful way to cope with this issue. As minerals are usually not found alone but aggregated in ores, MRIO models can indirectly capture this mineral footprint through ore mining and the first industrial processes, transforming ore into minerals. The MRIO models applied in this study can calculate this ore footprint across various ore classifications (cf. Table S5 in SI), and they encompass all 27 EU member states individually, ensuring a precise capture of the European Union's final demand.

To initiate our analysis, we sourced mineral production data from two well recognized sources for mineral production: the World Mining Data (WMD), an annual compilation by the Austrian Federal Ministry of Agriculture, Regions, and Tourism detailing the production metrics of 65 mineral commodities across 168 nations (Reichl and Schatz, 2021) that we cross-checked with the United States Geological Survey (USGS) data (United States Geological Survey, 2021). The International Energy Agency (IEA) report from May 2021 highlighted 35 critical minerals for the energy transition (IEA, 2021a). Our research focuses on 34 of these, excluding arsenic due to its intricate model integration and marginal relevance in footprint determination. The mineral production data were gathered for each of the 34 minerals, detailed at the country level and for the three years considered in the study (2017, 2018, and 2019). Each mineral is then associated with an existing ore category to be estimated from the ore footprint calculated with the MRIO models. Several ore categories were disaggregated on EXIOBASE to increase the precision of the study. (Cf. detailed results in SI_S1 1.1–1.3).

The EU ore footprint calculated is the part of the ore produced per country and ore type dedicated to the EU consumption. Then the EU mineral footprint is calculated for each country and each mineral by multiplying the mineral production weight per producing country (obtained from WMD and USGS sources) by the ore part dedicated to the EU consumption of the corresponding ore for this country (obtained from the ore footprint). Even if mining transformation activities mainly occur in mining countries, a country may extract ore without processing the minerals afterwards or inversely (as illustrated with Zimbabwe in Fig. 1). For further details on both cases, cf. SI_S1 1.4.

### 3.2. The EU mineral footprint for clean energy technologies

The footprint of the EU demand for clean energy technologies is estimated from the footprint of the total EU demand combined with mineral requirements data and energy systems transition scenarios published by the IEA (IEA, 2021a, 2020). The IEA published the mineral requirements for clean energy technologies in 2020, 2030, and 2040. The requirements for 2030 and 2040 are based on two energy transition scenarios developed by the IEA: the Stated Policies Scenario (STEPS) and the Sustainable Development Scenario (SDS). The STEPS reflects the current policies in place that would lead to a 2.6 °C temperature rise in 2100 compared to pre-industrial levels and capture the "Fit for 55 package" for the EU, as the IEA explicitly mentions it. The SDS considers that advanced economies will reach net zero emissions by 2050, China will reach it by 2060, and all other countries by 2070. It projects a temperature rise of 1.6 °C in 2100. For more information cf. SI_S1 1.5. The results are the mineral production weight per country and per mineral type for clean energy technologies in the EU (see Fig. 1, right part, mineral demand related/not related to clean energy production with a final consumption located in EU).

### 3.3. Gauging the social and environmental impacts of the EU mineral footprint for clean energy technologies

Given the MRIO models structural design and granularity, environmental and social impact quantification need to be executed at the ore extraction level. Via the mineral footprint, we have indeed quantified the critical mineral EU footprint in ore extraction but for all critical mineral end uses and not clean energy technologies specifically. Additionally, a notable constraint of the MRIO models is their formulation based on financial flows. This necessitates an estimation of the financial flow that corresponds to ore extraction, which subsequently transforms into critical minerals earmarked for clean energy technologies within the EU. This is done in two stages. First, we assessed the ore footprint of clean energy technologies in the EU from the mineral footprint calculated at the previous stage. Then, the financial output was calculated by combining this ore footprint and the total ore extraction attributed to each mining sector.

Considering one ore $A$, which produces several minerals $\mu_i \in M$

included in the study, and produced in several countries $C$, the quantity of ore A extracted for the EU consumption is:

$$T_{A,W} = \sum_{C} T_{A,C} \quad (1)$$

and the quantity of ore A extracted for clean energy technologies in the EU only is:

$$T_{A,W,E} = \sum_{C} T_{A,C,E} \quad (2)$$

Where:

- $T_{A,W}$ is the quantity of ore A extracted worldwide for the total EU consumption, in tons
- $T_{A,C}$ is the quantity of ore A extracted in country C for the total EU consumption, in tons
- $T_{A,W,E}$ is the quantity of ore A extracted worldwide for clean energy technologies in the EU, in tons
- $T_{A,C,E}$ is the quantity of ore A extracted in country C for clean energy technologies in the EU, in tons

From the literature, we have compiled the different ore to mineral ratios, that are the ratios to determine the required quantity of ore extracted to produce one weight unit of mineral. (For detailed results cf. SI_S1 1.6). And the quantity of ore A extracted in country C for clean energy technologies in the EU can be expressed as:

$$T_{A,C,E} = \sum_{i} \frac{T_{\mu_i,C,E}}{o_{A,\mu_i}} \quad (3)$$

Where:

- $T_{\mu_i,C,E} \in$ M is the quantity of mineral $i$ produced in country C for clean energy technologies in the EU, in tons
- $o_{A,\mu_i}$ is the ore-to-mineral weight ratio between the ore A and the mineral $\mu_i \in$ M.

The mineral quantity produced for clean energy technologies is expressed in function of the total mineral quantity produced for the EU as:

$$T_{\mu_i,C,E} = r_{\mu_i} * T_{\mu_i,C} \quad (4)$$

Where:

- $r_{\mu_i}$ is the weight ratio of the mineral $i$ between the part of the mineral $i$ consumed in EU for clean energy technologies only and the total EU consumption of the mineral $i$

Combining Equations (2), 3 and 4, we get:

$$T_{A,W,E} = \sum_{C} \sum_{i} \frac{T_{\mu_i,C} * r_{\mu_i}}{o_{A\mu_i}} \quad (5)$$

$$T_{A,W,E} = \sum_{i} \frac{T_{\mu_i} * r_{\mu_i}}{o_{A\mu_i}} \quad (6)$$

The ratio $R_A$ is defined as the ratio between the ore extracted for the consumption of clean energy technologies only in the EU and the total ore extracted for the consumption in the EU. Therefore, this ratio can be written as:

$$R_A = \frac{T_{A,W,E}}{T_{A,W}} \quad (7)$$

using equations (6) and (7), this ratio $R_A$ can be written as:

$$R_A = \frac{\sum_i \frac{T_{\mu_i} * r_{\mu_i}}{o_{A\mu_i}}}{T_{A,W}} \quad (8)$$

For each ore, the ratio defined in Equation (8) is used to estimate the part of the sector's financial output driven by the EU consumption of clean energy technologies. Some individual adjustments are needed for ores for which there are one or several by-products and for which no reliable information was found for the ore to mineral ratio (cf. SI_SI 1.7).

It should additionally be emphasized that, as highlighted in the introduction section, accurately assessing the mineral footprint can be challenging due to geographical disparities between the locations of ore extraction and mineral transformation. Nonetheless, the innovative aspect of our method, as demonstrated through Equations (5)–(8), effectively addresses this issue.

Equation (8) implicitly assumes that all ores included in the same MRIO sector have the same financial value. We have increased this approach's precision by further detailing the financial value for one sector:"*Mining of lead, zinc, tin ores and concentrates*". We have selected this sector due to its crucial aspect in clean energy technologies and because the financial value is well documented since it is included in the London Metal Exchange (United States Geological Survey, 2021); cf. SI_S1 1.8 for further detail.

## 4. Results

### 4.1. EU ore and mineral footprints

The present study offers a novel perspective on the EU mineral footprint, deviating from the conventional approach, which typically hinges on the ore footprint. Our results, summarized in Table 2, underscore a unique pattern within the European-located footprint, exhibiting a significant contraction when juxtaposed with both footprints. The quantification of uncertainties related to these findings is outlined utilizing both MRIO models considered in this study. Factoring in the inherent uncertainties, the EU mineral footprint manifests a median of 34 % located within Europe,[2] presenting a stark contrast to the median of 62 % situated in Europe as evidenced by the ore footprint.

Our analysis reveals that the African continent is witnessing the most dramatic upsurge between the perspectives of ore and mineral footprints. Along with the Asia-Pacific region, it establishes itself as the first region outside of Europe, contributing to the EU's mineral footprint. To

**Table 2**
Comparative Footprints of EU Ore, General Mineral, and Minerals for Clean Energy Technologies for 2019. Values represent weights of extracted material, with percentages indicating regional share of extraction location.

| Locations | Ore footprint | Mineral footprint | Mineral footprint for EU clean energy technologies only |
|---|---|---|---|
| *Year* | *2019* | *2019* | *2019* |
| Africa | 2–8 % | 24–29 % | 13–14 % |
| Asia-Pacific | 17–26 % | 18–26 % | 15–20 % |
| Europe | 50–71 % | 34–34 % | 29–37 % |
| Middle East | 3–7 % | 0.6–1 % | 1–1 % |
| North America | 2–3 % | 4–5 % | 6–7 % |
| South America | 3–5 % | 12–12 % | 26–32 % |
| Total (in millions of tons) | 4,021–4,061 | 7.5–9.8 | 1.07–1.09 |

[2] In the manuscript, the term "Europe" in the context of footprint location refers specifically to the geographical region of the European continent. However, when "Europe" is used as an adjective or in other contexts, for instance "European Energy Sector", it refers to the different countries of the European Union.

decipher the divergence between the ore and mineral footprints, we focus on the ores' mineral composition. Notably, Copper is recovered with a weight ratio of around $10^{-2}$ from copper ores while Selenium and Tellurium are recovered from the same ore with a weight ratio respectively of around $5.10^{-5}$ and $2.10^{-5}$ (Bleiwas, 2010). Hence, a first hypothesis could be the The different mineral content of ores and the different metal grades of minerals. Another plausible explanation for this disparity is that the recovery of by-products is contingent on the specific ore deposit's characteristics, whereby only selected ores with sufficiently high concentrations of these elements are extracted for economic reasons (Bleiwas, 2010). Our findings underscore the significance of precisely scoping the relevant ore extraction activities when estimating the mineral footprint of critical minerals.

The mineral extraction required for producing clean energy technologies is crucial to transitioning towards a low-carbon future. The last column in Table 2 presents the 2019 mineral footprint for EU clean energy technologies only. Despite Europe contributing roughly 33 % to this specific footprint, the same as the entire EU mineral footprint (34 %), geographical contribution shows a marked difference under this clean energy lens (Table 2). There is a notable shift in contributions from South America and Africa, with the former's contribution increasing from 12 % to 29 %, while Africa's contribution decreases from 26 % to 14 %.

Table 3 shows that different scenarios and timeframes significantly affect the global quantity and distribution of the EU's mineral footprint for clean energy technologies. Specifically, the SDS results in a total extraction weight that is 1.3 to 1.4 times higher than the STEPS scenario. Additionally, the choice of scenario has a slightly greater impact on the geographical distribution of the mineral footprint than the timeframe does. Projected to 2030 and 2040, the EU mineral footprint for the energy transition reveals a trend of increasing contributions from all regions. However, this is coupled with a fluctuating share of the footprint, indicating regional disparities. Europe's share is expected to witness a marginal downward trend, decreasing from 33 % in 2019 to 29–32 % in 2040, depending on the scenario. On the other hand, Asia-Pacific is projected to experience the most significant growth, increasing from 18 % in 2019 to 27 % in 2040 under the SDS. This upsurge is tied to the region's significant contribution to the EU's graphite, copper, and nickel footprint. By 2040, Europe, Asia-Pacific, and South America collectively would account for nearly 80 % of the total mineral footprint weight for EU clean energy technologies.

A few key players lead country-specific contributions within these regions. For instance, South America's contributions are driven by Chile and Peru, major contributors to the EU's copper footprint, while in the Asia-Pacific region, China - primarily through graphite - and Australia, through lithium, are key contributors. Russia and Poland are leading contributors within Europe, contributing to the copper footprint.

**Table 3**
EU mineral footprint for clean energy technologies only. Results for 2019 and projected EU mineral footprint for clean energy technologies for 2030 and 2040 based on different IEA scenarios. Values represent weights of extracted material, with percentages indicating regional share of extraction location.

| Locations | Mineral footprint for clean energy technologies only | | | | |
|---|---|---|---|---|---|
| | | STEPS | | SDS | |
| *Year* | *2019* | *2030* | *2040* | *2030* | *2040* |
| Africa | 13–14 % | 15—15 % | 13—14 % | 15–15 % | 14–15 % |
| Asia-Pacific | 15–20 % | 20–24 % | 20–24 % | 23 – 28 % | 25–29 % |
| Europe | 29–37 % | 28–35 % | 28–35 % | 27–33 % | 27–32 % |
| Middle East | 1–1 % | 1–1 % | 1–1 % | 1–1 % | 1–1 % |
| North America | 6–7 % | 5–7 % | 5–7 % | 5–7 % | 4–7 % |
| South America | 26–32 % | 23–27 % | 23–28 % | 21–25 % | 21–25 % |
| Total (in millions of tons) | 1.07–1.09 | 1.63–1.67 | 1.73–1.78 | 2.23–2.30 | 2.46–2.54 |

For certain minerals, the demand in 2040 for energy transition is expected to surpass their current total EU demand for all end-uses. Those minerals and their related metals include gallium, vanadium, lithium, graphite, cobalt, nickel, neodymium, and other rare-earth elements. Gallium, lithium, and graphite are projected to lead the demand with their consumption in 2040 for clean energy technologies anticipated to be more than twice the current total EU footprint for these minerals under both scenarios and models (for results detailed at sectoral level cf. SI_S1 1.9).

Our findings are consistent with previous studies by Deetman et al. (2018), which showed increased demand for copper, neodymium, and tantalum for electronic appliances, cars, and renewable energy by 2050. Valero et al. (2018) also identified 13 high-risk elements, including cobalt, lithium, nickel, and gallium, which could pose a bottleneck for the future global development of clean energy technologies. However, they considered vanadium and rare earth elements without risk and medium risk, which differs from our findings.

### 4.2. *Environmental indicators*

Regarding the environmental indicators and impacts, this study primarily focuses on climate change impacts. Water withdrawal indicators are also evaluated but not detailed herein; key findings are briefly summarised below (Section 4.2.2). It is important to note that some critical environmental and human health impacts from the mining industry have not been included: i.e., impacts associated with emissions of heavy metal pollutants, biodiversity destruction, deforestation and land-use change, and air pollution around the mining area. The lack of those impacts is due to either their absence from the MRIO environmental indicators or their inaccurate level of aggregation to describe those impacts. As such, it was not possible to calculate the impacts listed above without significant additional work to integrate relevant data into the MRIO currently available.

#### 4.2.1. *Climate change impacts*

The mining sector worldwide, tasked with extracting resources for ultimate consumption in the European Union's energy sector, accounted for direct climate change impacts (scope 1, direct GHG emissions) between 600 and 1700 kilotons CO2 equivalent (kt-CO2eq) in 2019. The escalating demand for minerals necessary for clean energy technologies could potentially amplify these direct emissions by a factor ranging from 1.6 to 1.9 by 2030 and 2.4 to 4.9 by 2040, according to the range of results (Fig. 2.A).This impact assessment of the mining sector broadens when considering the entirety of the supply chains prior to the final use within the EU (scope 1, 2 and partial scope 3, direct and indirect GHG emissions). Our projections estimate an additional 3.2 to 7.6 million tons of CO2 equivalent (Mt-CO2eq) by 2030 and an increase of 8.2 to 14.3 Mt-CO2eq by 2040, relative to 2019 (Fig. 2A).

Nonetheless, these figures should be contextualized within the broader framework of GHG emissions reduction attainable through the EU's energy transition. For instance, under the STEPS Scenario, a reduction of 327 Mt-CO2eq is anticipated in the EU's electricity and heat sectors by 2030, compared to the 2019 levels. Thus, the overall impact of the mineral demand for clean energy technologies should be considered alongside these potential reductions in emissions due to the transition to clean energy.

In 2019, the primary locations of direct and indirect GHG emissions from mining activities extracting resources for ultimate consumption in the EU's energy sector were the Asia-Pacific and Europe regions, as visualized in Fig. 2B. Based on median projections from the Eora and EXIOBASE models, these two regions accounted for approximately 37 % and 27 % of total emissions, respectively. However, the pattern of contributions from these regions is anticipated to diverge over time. Europe's emissions are projected to decrease to 17 % by 2040 under the SDS, while an increase is expected from the Asia-Pacific region. Africa

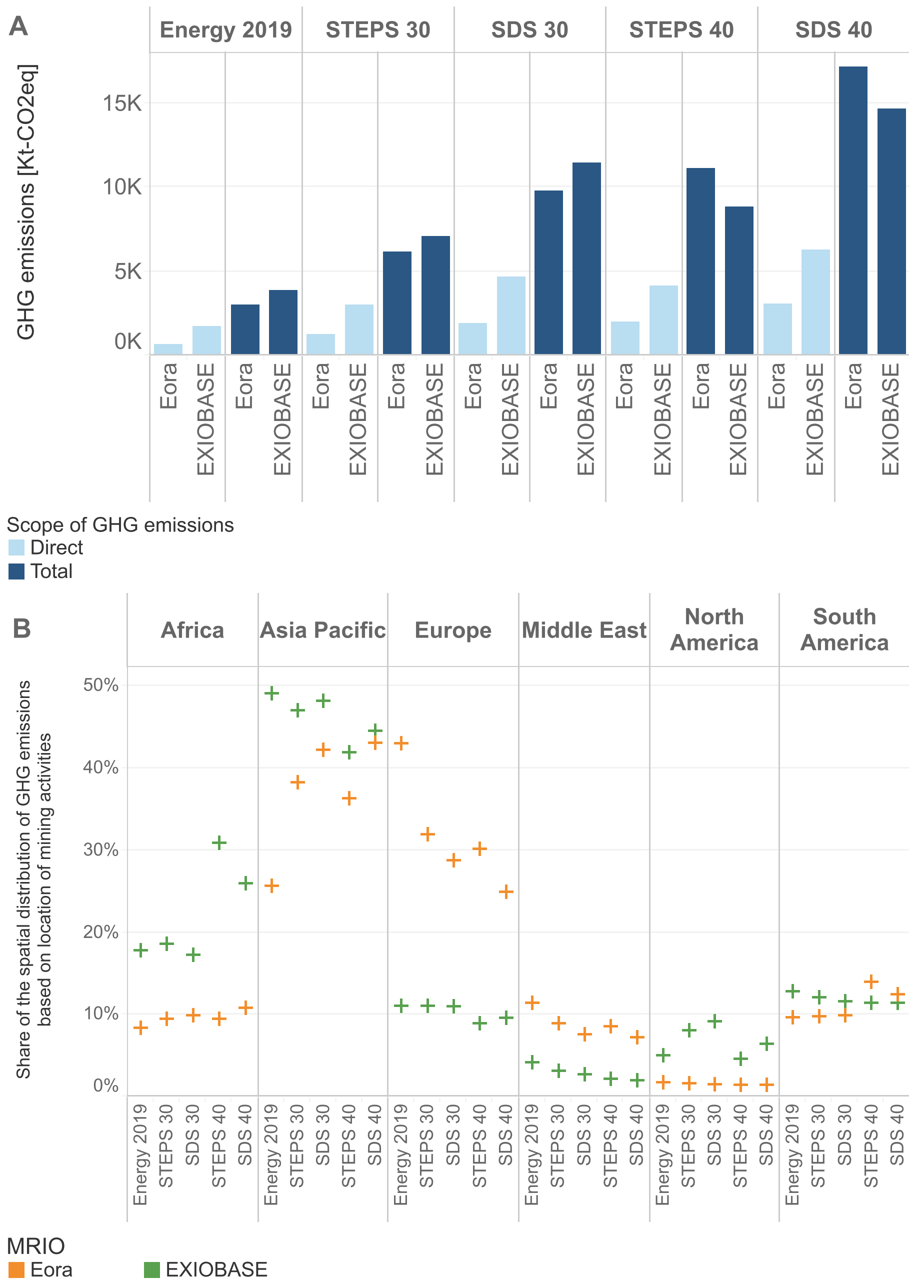



**Fig. 2.** Fig. 2A: Assessing the direct (direct GHG emissions, scope 1) and total (direct and indirect GHG emissions, scopes 1, 2 and partial scope 3) climate change impacts stemming from global mining operations that are performed at the initial stages of the clean energy supply chain utilized in the EU's energy transition regarding 2019 and both scenarios (STEPS and SDS), measured in thousands of tons of CO2 equivalent. Fig. 2B: Geographical distribution of the total climate change impacts presented in Fig. 2A.

and South America each contributed 10–15 % of total emissions in 2019, with Africa's share forecasted to rise to nearly 20 % by 2040.

By 2040, over 80 % of direct and indirect GHG emissions are expected to be related to mining activities outside of Europe for both scenarios. The spatial disaggregation of the Eora model enables a country-level analysis of climate change impacts, as demonstrated in Fig. 3A and 3B. These figures illustrate that the primary contributors to the Asia-Pacific region's mining sector's GHG emissions are China and Australia. In Fig. 3B, Algeria, India, and Colombia enter the top 10 emitting countries, with Algeria ranking second in total GHG emissions before China. However, this observation warrants further exploration due to the potential implications of the original from the MRIO input–output transactions database itself.

Climate change impacts from global mining operations at the initial stages of the clean energy supply chain utilized in the EU's energy transition are more international than the mineral weight footprint. These impacts are spread worldwide, with top contributing countries for both impact categories (direct and indirect) located in every world region except the Middle East. However, leading countries emerged for both impact categories, such as Australia and China, and frontrunners exist in every world region (South Africa, Brazil, Ukraine, and the United States). While the climate change impacts are distributed globally, most are concentrated in a limited number of countries.

Finally, mining emissions are expected to be heavily concentrated at the country level by 2040. For instance, under the SDS, the top 10 emitting countries account for 76 % of total emissions in 2040.

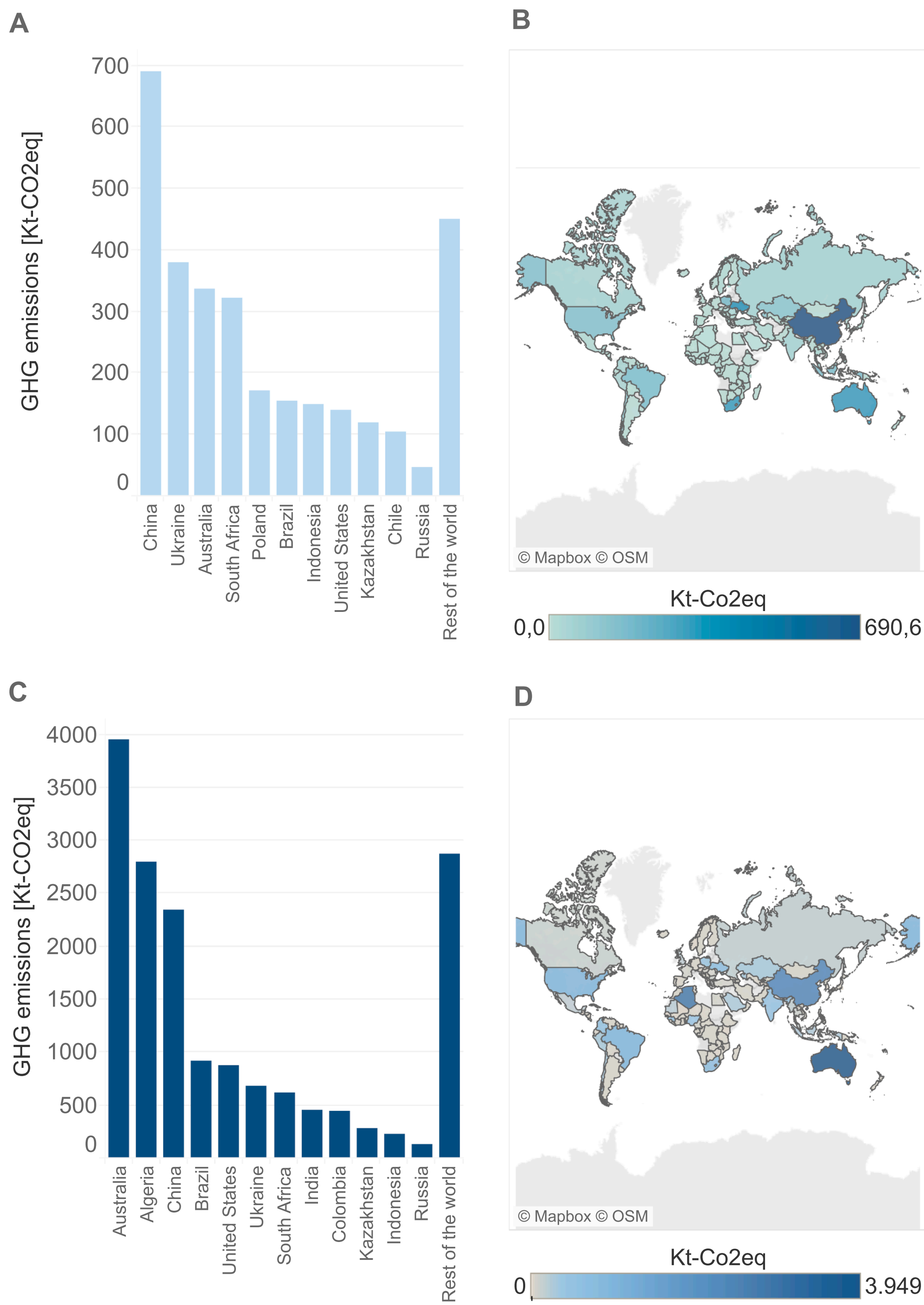



**Fig. 3.** Climate change impacts from initial stages of the clean energy supply chain utilized in the EU's energy transition in 2040 regarding the SDS. 3A direct impact detailed for top countries, 3B detailed direct impacts by country, 3C total impact detailed for top countries, 3D Detailed total impacts by country. Results are in kt-CO2eq, computed using Eora.

#### 4.2.2. *Water withdrawal indicators*

In 2019, direct blue water consumption was estimated to span a range between 0.6 and 1.6 million cubic meters. As we move forward, this direct consumption is projected to culminate in an estimated consumption of 3.2 to 3.8 million cubic meters by 2040. However, when one accounts for indirect water consumption, the figures skyrocket, multiplied by a factor of 10 to 20. To put it in perspective, the combined direct and indirect blue water consumption was projected between 12 and 15 million cubic meters in 2019. Under the Sustainable Development Scenario (SDS), by 2040, this combined consumption is predicted to soar to around 70 million cubic meters. For a more detailed breakdown of these figures, readers can refer to SI_S1 1.10.

Furthermore, based on data extrapolated from Eora, a mere five countries are responsible for more than 60 % of this total blue water consumption, as visually represented in Fig. 4. These include Australia, with Kazakhstan and Ukraine not far behind, followed by Algeria and Columbia in the anticipated footprint for 2040, aligned with the SDS.

### 4.3. Social impacts, vulnerability to modern slavery

Mineral extraction by on-ground mining workforces is a key component in the global supply chain, meeting the mineral needs of the European Union's clean energy technologies. In 2019, approximately 71,000 full-time equivalents (FTE) workers were engaged in ore extraction, comprising about 0.4 % of the global mining workforce that year. The DRC, Russia, and Indonesia ranked as the top three nations with the most FTEs in this sector. However, the mining sector is fraught with substantial risks, notably modern slavery, jeopardizing the safety and well-being of its workers. To measure this risk, we employed the Global Slavery Index (GSI) vulnerability model. Rather than directly quantifying modern slavery instances, this model pinpoints factors predicting or explaining modern slavery prevalence. The GSI scores are normalized, with 100 symbolizing the utmost vulnerability to modern slavery.

As depicted in Fig. 5, about 23 % of the 71,000 FTEs operate in nations with high susceptibility to modern slavery. The DRC, Cameroon, and Nigeria showcase the most pronounced risks in this regard. Peering into 2040, both STEPS and SDS anticipate an upswing in the FTE on-ground mining workforce. The STEPS scenario forecasts an addition of roughly 116,000 FTEs, while the SDS projects around 233,000 more. Most of this augmented workforce will likely be in nations currently displaying a moderate slavery vulnerability, indicated by GSI scores ranging from 50 to 60 (cf. Fig. 6.A) Yet, if the 2040 distribution of countries with high vulnerability to modern slavery mirrors that of 2019, FTEs in high-risk nations could see a marked spike. An estimated 15,000 (under the STEPS scenario) to 29,000 (under the SDS) additional FTEs might be stationed in high-risk regions to cater to the EU's mineral demands for clean energy (cf. Fig. 6.A). This implies a potential two to threefold increase in the population at risk (cf. Fig. 6.B). Notably, certain nations like the Central African Republic or Chad display an acute vulnerability to modern slavery but employ very few workers for ore extraction meant for the EU. In contrast, others like the DRC present both high risks and substantial worker counts. Therefore, a precise evaluation of the at-risk populace, resulting from specific consumption patterns, is essential. This will inform effective public policies and due diligence measures, aiming to alleviate these looming threats.

## 5. Discussion

### 5.1. EU mineral footprint

This research underscores the necessity for comprehensive footprint delineation, particularly when investigating issues requiring an in-depth understanding of transformation processes along the supply chains and economic interlinkages. As such, in the case of critical minerals, traditional approaches mainly focus on ore extraction, overlooking subsequent supply chain stages and their impact on the footprint. As a result, these approaches might miss some nuances that are key to calculate a detailed footprint picture. Table 4 contrasts the global ore extraction locations for selected critical minerals as reported by IRENA in 2023 (IRENA, 2023), which takes a production-based perspective, with this study's findings concerning the EU's mineral footprints, which adopt a consumption-based perspective.

Despite a two-year data gap that could explain minor variances, our results largely concur with IRENA's values. However, we observe notable deviations in the EU's mineral footprint for several countries when compared to global ore extraction patterns. These deviations can be attributed to specific economic relationships with the EU and complexities in mineral refining processes.

Our study was cross-referenced with the European Commission's

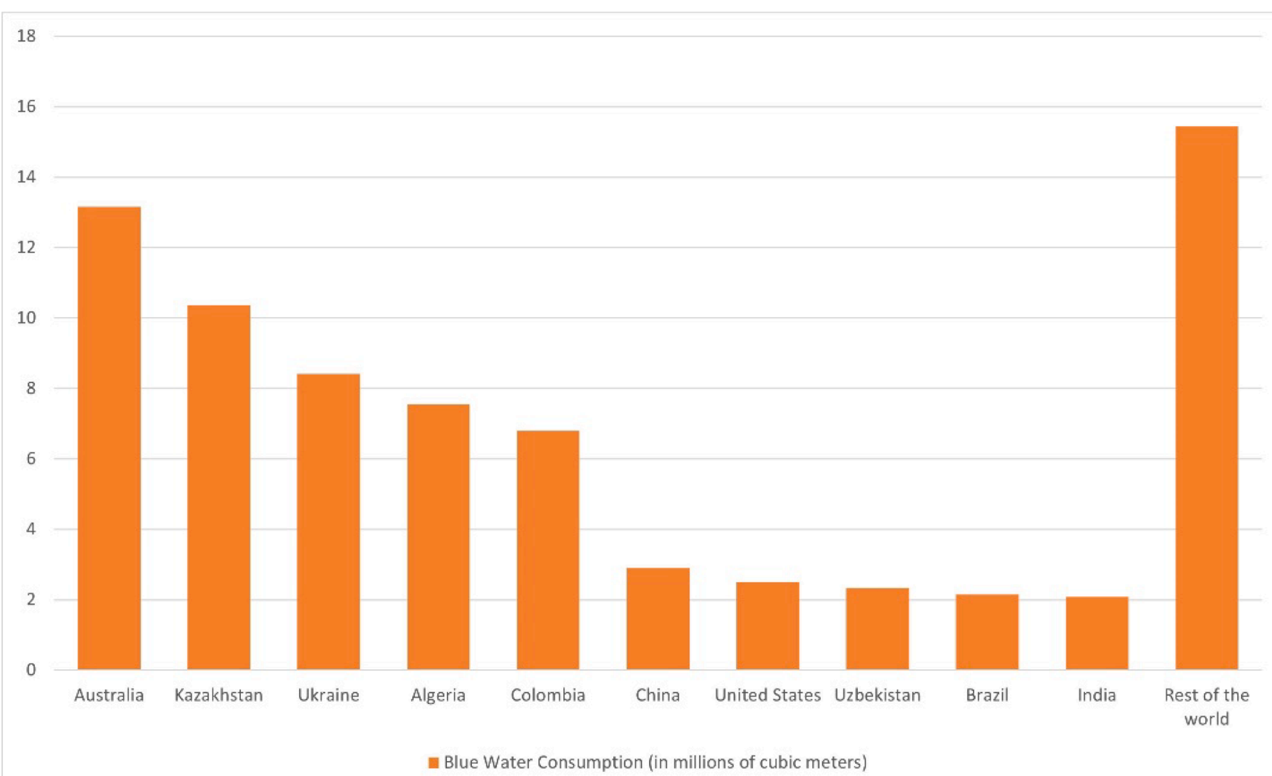



**Fig. 4.** Country distribution of total blue water consumption from initial stages of the clean energy supply chain utilized in the EU's energy transition in 2040 regarding the SDS. Results are expressed in millions of cubic meters, computed using Eora. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

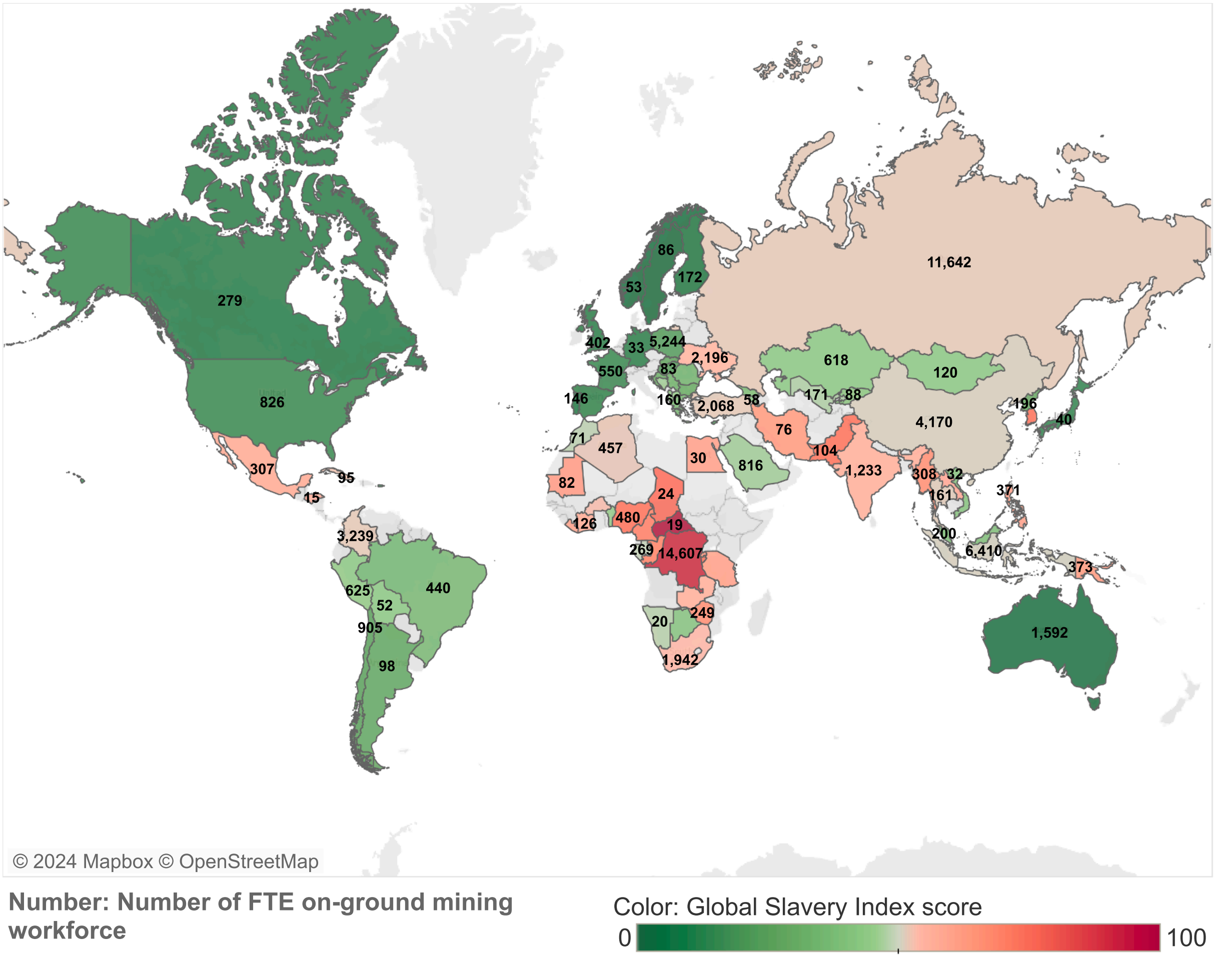



**Fig. 5.** Mapping the Intersection of Mineral Demand in the European Energy Sector and Vulnerability to Modern Slavery in the 2019 On-Ground Mining Workforce: This geographic visualization illustrates the global distribution of the 2019 on-ground mining workforce actively involved in extracting minerals feeding into the European energy sector's supply chain. Numerical annotations indicate the workforce size in each region, presented in full-time equivalent (FTE). Meanwhile, the color gradient of the map serves as a visual indicator of the Global Slavery Index (GSI) score, capturing the risk of vulnerability to modern slavery. Regions with the highest vulnerability are marked in an alarming red, while areas with the least risk are depicted in a reassuring dark green. This representation aids in discerning regions of concentrated labor that also face heightened risks of modern slavery, a crucial insight for targeted policy and intervention. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

March 2023 report on Critical Raw Materials for the EU (European Commission, 2023a). Both studies employ different methodologies but have areas where comparison is possible. The Commission's report relies on trade data, making it more precise but differently focused than our study, as it differentiates between extraction and processing source while we unify them into the *mineral footprint*. While a direct comparison is not feasible, Annex 8 of the EU Commission's report offers a narrower scope for comparison by isolating the extractive footprints of Tantalum and Zirconium (European Commission, 2023a). Despite these methodological differences and varying time frames, there is a relatively good agreement between our findings and the Commission's for these specific minerals, as shown in Table 4.

In light of this, our findings uncover pronounced footprint discrepancies when evaluated within their specific contexts. As Table 3 demonstrates, while Europe contributes to 60 % of the EU's ore extraction footprint, its role in the mineral footprint for the 34 evaluated minerals is reduced to merely 35 %.

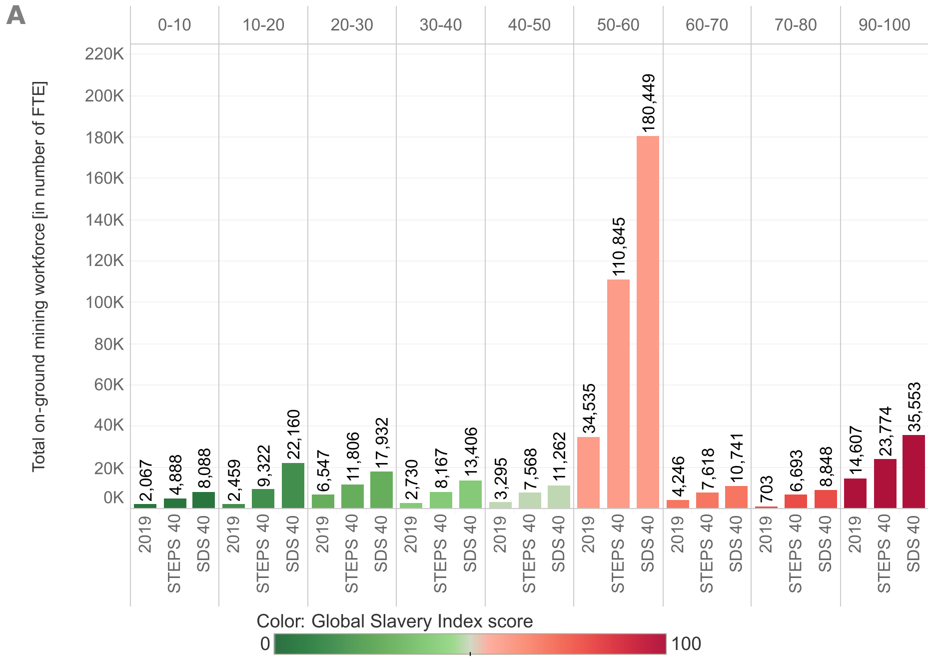
As detailed in Section 4.1, the projected EU demand for some critical minerals is anticipated to surpass their 2019 EU demand across all end-uses by 2040. This trend is particularly evident for some minerals and some metals like gallium, lithium, graphite, iridium, and neodymium. On a geographical scale, Australia, South Africa, and China stand out as primary suppliers. Securing these minerals for the energy transition might entail challenges, including potential conflicts with other end-uses, both within the EU and globally. Moreover, the mineral footprint consumption-based approach offers crucial insights, such as highlighting Myanmar's significant role in supplying Neodymium to the EU — a fact that might not be as evident when looking at global supply metrics (see Table 4).

In terms of temporality, as depicted in Table 3, these challenges may materialize as early as 2030. The scale of required actions should be proportionate to the desired outcomes; for instance, an ambitious scenario (e.g., SDS) would necessitate immediate and ambitious interventions.

### *5.2. Environmental and social indicators*

Understanding the mineral footprint is crucial for assessing both environmental and social impacts as well as contextualise them at global and national scale. For instance, while Australia is projected to see an increase in GHG emissions by 2040 due to the EU's energy transition, the increase will be less than 1 % of its 2019 levels. Given the EU's goal to cut global emissions, such relative increases require nuanced analysis.

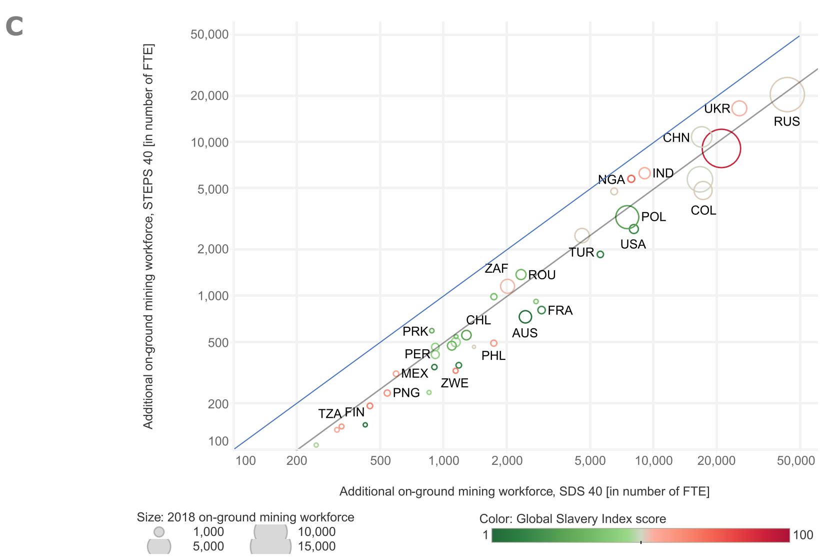
Water withdrawal's impact varies based on the water stress conditions of the specific mining basin. Usually mining contributes to less than 0.1 % to total water consumption (Meißner, 2021), in some mining




B

| Global Slavery Index score | 2019 | STEPS 30 | STEPS 40 | SDS 30 | SDS 40 |
|---|---|---|---|---|---|
| 0-10 | 1.0 | 1.7 | 2.4 | 2.8 | 3.9 |
| 10-20 | 1.0 | 3.8 | 3.8 | 7.3 | 9.0 |
| 20-30 | 1.0 | 1.6 | 1.8 | 2.2 | 2.7 |
| 30-40 | 1.0 | 2.1 | 3.0 | 3.3 | 4.9 |
| 40-50 | 1.0 | 1.6 | 2.3 | 2.4 | 3.4 |
| 50-60 | 1.0 | 2.0 | 3.2 | 3.2 | 5.2 |
| 60-70 | 1.0 | 1.3 | 1.8 | 2.1 | 2.5 |
| 70-100 | 1.0 | 1.6 | 2.0 | 2.2 | 2.9 |

Color: Global Slavery Index score
0 100




(caption on next page)

**Fig. 6.** Evolution and projection of the on-ground mining workforce based on GSI vulnerability to modern slavery. Fig. 6A: A comparative visualization of the anticipated on-ground mining workforce for both scenarios (STEPS and SDS) in 2040 against the 2019 workforce, categorized by each country's GSI 2019 grade, indicating vulnerability to modern slavery. Fig. 6B: A detailed expansion of Fig. 6A, providing a breakdown for 2030 and 2040. This section quantifies the ratio of workforce multiplication relative to the 2019 baseline. The visualization's color gradient is dictated by the GSI 2019 grade of the respective country where the additional workforce is anticipated. Fig. 6C: A scatter plot illustrating the projected additional on-ground mining workforce for both scenarios (STEPS and SDS) in 2040. Bubble sizes represent the 2019 on-ground mining workforce, while their colors are determined by the GSI 2019 grade (presented on a logarithmic scale), emphasizing the scale of workforce in relation to vulnerability to modern slavery. In grey the trend line and in blue the line x = y. A notable observation from the plot is the minimal sensitivity difference between scenarios (STEPS and SDS), other than a distinct shift between the two. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

areas, water use by mining activities sometimes surpasses availability. Half of the world's copper and lithium production, which are central to our study, are situated in water-scarce regions (IRENA, 2023). Notably impacted zones include the Loa Basin in Australia, the Issyk-Kul basin in Kazakhstan, and select regions in South Africa, and Chile. Increased mining driven by the EU energy transition, especially in Australia and Kazakhstan (see Fig. 4), could intensify these water challenges, potentially damaging ecosystems, igniting community disputes, and even jeopardizing the mining operations crucial for the EU energy shift. IRENA experts even equate water scarcity risks to significant challenges like geological scarcity or export restrictions highlighting the need for comprehensive studies addressing both supply and environmental dimensions (IRENA, 2023).

Our study, using a unique methodology, estimates 15,000 workers from large scale and industrial mining (LSM) activities in the EU's clean energy supply chains are at high risk of modern slavery. This aligns in scale but differs in geographical focus from a 2022 study by Malik et al. (Malik et al., 2022). Globally, LSM is a sector that do not present a significantly high fatal accident ratio. According to the study by Berthet et al. (2024), when compared to the 155 other sectors in Exiobase, the aggregation of the LSM sectors concerned by this study ranks globally 51st in terms of fatal accident ratio. However, it is particularly important to note that ASM activities present a range of social and environmental risks as well as health risks significantly higher compared to LSM (Baumann-Pauly, 2020; Faber et al., 2017; Gyamfi et al., 2019; Landrigan et al., 2022; Sovacool, 2019). The sector's informal trading bypasses official channels, leading to revenue loss for governments (Noetstaller et al., 1995; Tarras-Wahlberg, 2002) and it potentially funds criminal or extremist groups, heightening conflict risks. ASM makes up 15–20 % of the global mineral yields, is less productive than industrial mining and carries disproportionately higher risks (Buxton, 2013; Sovacool, 2019). Our projections suggest that the number of at-risk workers could increase 3.5 to 6.8 times by 2040, when considering both official and ASM miners— significantly above industrial mining statistics alone (cf. Fig. 6.A and 6.B). This would lead up to 89,000 additional mining workers (official and ASM) working in 2040 for the EU's clean energy supply chains in countries where they would be exposed to high risk of modern slavery (mainly located in Africa). Hence, it is crucial to note that the data displayed in section 4.4 primarily covers LSM activities, thus presenting a conservative estimate.

Last, critical minerals mining activities often overlap with indigenous territories, putting these communities at risk. The MRIO approach, while identifying affected nations, doesn't precisely locate specific activities within them. As such, the mineral footprint is the starting point for in-depth local analyses crucial for proactive community engagement.

### 5.3. Uncertainties and limitations

While integrating physical and economic flows, our study was confronted with inherent limitations of MRIO databases. These databases, essential for our analysis, tend to be more effective in capturing global overviews or aggregated mineral categories rather than offering detailed insights into individual results. This limitation is particularly evident in the variability, which we observed in the ranking and share of top minerals across different databases (see SI_S1 1.13), thus underscoring the challenge in achieving consistent environmental impact assessments. Additionally, we integrated physical and economic flows, presuming consistent financial values across ores within a sector (see SI_S1 1.8). Enhanced precision at each mineral/country interaction is essential for accuracy.

Another critical aspect is the static nature of MRIO models. These models, while robust in certain applications, only provide a snapshot of international trade, limiting the ability to project future scenarios dynamically. This static view means that the projections for 2030 and 2040 under various scenarios might not fully encapsulate potential changes in global demand or shifts in international trade structures. It also presupposes a constant supply of minerals, an assumption that may not hold true under evolving geopolitical and economic conditions.

Those limitations are for example visible through the current geopolitical issue between Ukraine and Russia. The scope of our study is anterior to the 2022 Russian invasion of Ukraine. Eora's data marked Ukraine as Europe's top emissions contributor, mainly from nickel-related activities. Ukraine specialized in converting nickel to ferronickel, a process not necessarily aligned with the primary nickel demand from Lithium-ion batteries. This situation, coupled with potential post-invasion shifts, emphasizes the challenges in such time-specific and sector-specific studies. Despite these limitations, our approach offers the most detailed consumption-based insights currently available.

To address these remaining challenges in future research, promising track is to explore hybrid models. For instance, models may be built by combining MRIO mineral footprint with MFA data, potentially offering a more precise mapping of supply chains. This approach could enhance the granularity of the mineral footprint analysis, enabling a more detailed understanding of the origins and destinations of ores in the processing stages. Additionally, combining MRIO mineral footprint with Computable General Equilibrium (CGE) models could help better capture dynamically projected scenarios or potential disruptions in the supply chains.

### 5.4. Implications in the context of the EU green deal

The EU Green Deal, designed to promote social equity, may indirectly escalate the global risk of modern slavery in the mining sector due to an increased demand for some minerals essential for clean energy technologies. This demand varies: while some minerals like iridium could see their consumptions surge by a thousandfold by 2040, others may face more moderate increases. However, not all of these rising demands exert equal pressure on their EU's supply, with the scale of other end-uses playing a significant role. Specifically, seven minerals and metals, namely - gallium, vanadium, lithium, graphite, cobalt, nickel, and Rare Earth Elements (REEs) - are identified as having major supply risks as their projected requirements under the SDS for 2040 surpass their total 2019 EU demand. Additionally, some of these minerals and metals such as gallium, lithium, and graphite suffer from a lack of diversity in their global supply. This makes diversification challenging and it underscores the urgency of measures to mitigate their socio-environmental impacts. Last, cobalt, gallium, lithium, and nickel are generally identified to become bottlenecks globally in the development of green technologies and must also require particular attention (Valero et al., 2018; Watari et al., 2018).

**Table 4**
Comparative 2019 EU Footprints for selected critical minerals with the global 2022 production figures of those selected critical mineral from the last IRENA report and with the last 2023 European Commission's study on Critical Raw Materials for the EU. This table provides two key comparisons: first, it juxtaposes the EU's consumption-focused footprint with global production figures from the 2022 IRENA report; second, it contrasts the EU's consumption-based approach with the EU's trade data-based study from 2023. Values are calculated in weight of extracted material and the percentages on the table indicate regional share of extraction location.

| Selected critical materials | Mining countries | This study, 2019 EU mineral footprint | IRENA study, 2022 global mining countries (IRENA, 2023) | Critical Raw Materials for the EU study, 2023 EU Sourcing shares (European Commission, 2023a) |
|---|---|---|---|---|
| **Cobalt** | DRC | 76.2 % | 70.0 % | N/A |
| | Indonesia | 0.1 % | 5.4 % | |
| | Russian Federation | 10.1 % | 4.8 % | |
| | Australia | 1.2 % | 3.2 % | |
| | Canada | 0.8 % | 2.1 % | |
| | Cuba | 0.3 % | 2.0 % | |
| | Philippines | 0.6 % | 2.0 % | |
| | Others | 10.8 % | 10.5 % | |
| **Copper** | Chile | 27.5 % | 23.6 % | N/A |
| | Peru | 8.2 % | 10.0 % | |
| | DRC | 12.0 % | 10.0 % | |
| | China | 5.3 % | 8.6 % | |
| | USA | 3.9 % | 5.9 % | |
| | Russian Federation | 10.6 % | 4.5 % | |
| | Indonesia | 1.4 % | 4.1 % | |
| | Australia | 2.2 % | 3.7 % | |
| | Zambia | 0.9 % | 3.5 % | |
| | Mexico | 1.4 % | 3.3 % | |
| | Kazakhstan | 1.3 % | 2.6 % | |
| | Canada | 0.9 % | 2.4 % | |
| | Poland | 10.2 % | 1.7 % | |
| | Others | 14.2 % | 16.1 % | |
| **Graphite** | China | 61.0 % | 64.6 % | N/A |
| | Mozambique | 11.6 % | 12.9 % | |
| | Madagascar | 5.9 % | 8.4 % | |
| | Brazil | 4.8 % | 6.6 % | |
| | Others | 16.7 % | 7.5 % | |
| **Iridium** | South Africa | 89.0 % | 88.9 % | N/A |
| | Zimbabwe | 1.2 % | 8.1 % | |
| | Russian Federation | 8.9 % | 2.9 % | |
| | Others | 1.2 % | 0.1 % | |
| **Lithium** | Australia | 46.3 % | 46.9 % | N/A |
| | Chile | 33.6 % | 30.0 % | |
| | China | 6.5 % | 14.6 % | |
| | Argentina | 8.5 % | 4.7 % | |
| | Brazil | 0.5 % | 1.6 % | |
| | Others | 4.6 % | 2.2 % | |
| | Others | | | |
| **Neodymium** | China | 52.4 % | 45.8 % | N/A |
| | Australia | 9.31 % | 23.1 % | |
| | Myanmar | 19.0 % | 7.4 % | |
| | Brazil | 0.5 % | 4.4 % | |
| | India | 0.9 % | 2.1 % | |
| | Others | 17.9 % | 17.2 % | |
| **Tantalum** | DRC | N/A | 35.8 % | 35 % |
| | Rwanda | | 21.0 % | 17 % |
| | Brazil | | 6.2 % | 16 % |
| | Nigeria | | 17.7 % | 11 % |
| | China | | 3.3 % | 7 % |
| | Ethiopia | | 4.7 % | 4 % |
| | Mozambique | | 3.5 % | 3 % |
| | Australia | | 1.4 % | 2 % |
| | Russia | | 4.8 % | 2 % |
| | Burundi | | 0.8 % | 1 % |
| | Other | | 0.8 % | 1 % |
| **Zirconium** | South Africa | N/A | 21.5 % | 38 % |
| | Australia | | 33.4 % | 30 % |
| | Senegal | | 8.6 % | 11 % |
| | Mozambique | | 8.0 % | 10 % |
| | Morocco | | 0.1 % | 2 % |
| | Kenya | | 3.7 % | 2 % |
| | Ukraine | | 3.1 % | 1 % |
| | Madagascar | | 2.6 % | 1 % |
| | USA | | 6.3 % | 1 % |
| | Indonesia | | 2.1 % | 1 % |

#### 5.4.1. *A primary action lever: original production and imports*

To secure its future supply amid escalating mineral demands for the energy transition, the EU must diversify its critical mineral supply chains. This means both tapping into domestic production potential and forging partnerships with mineral-rich countries, ensuring adherence to high environmental and social standards. While the extraction stage is geographically constrained by ore locations, limiting diversification for many minerals, Europe has notable deposits of copper, zinc, lead, and lithium (Regueiro and Alonso-Jimenez, 2021). Bolstering mining activities demands policymakers to foster sector investments, streamline mining regulations, augment geological data access, and heighten social acceptance (França Pimenta et al., 2021). Given the challenge of enhancing social acceptance, policymakers must adopt inclusive decision-making, articulate local economic ramifications, and avert global environmental and social setbacks. Promoting technology and securing the "social license to operate" demands that European leaders spotlight best practices to build trust with citizens and investors. Additionally, this could also have positive spillover effects on the international market, as an intra-European market will pressure international competitors to increase their social and environmental standards and thus contribute to strengthening the level playing field for sustainable mining.

The EU's efforts to diversify and secure its raw material supply began with the Raw Materials Initiative (RMI) in 2008 (European Commission, 2008). The EU has made further strides with the Critical Raw Materials Act (CRMA) in 2023 (European Commission, 2023b), mandating that at least 10 percent of some raw materials should be domestically extracted by 2030. Despite these initiatives, the EU has not fully achieved its objectives (Regueiro and Alonso-Jimenez, 2021). Hence, a detailed study by Farooki et al. (2018) revealed that, particularly for base metals, there has been limited progress in increasing exploration expenditures in Europe, and no significant rise in production is anticipated. This is well illustrated by the fact the EU, which consumes 25–30 % of the world's metals, invested only roughly 4 % of the global exploration budget related to metallic mineral exploration in 2016 and this EU exploration budgets has decreased by 70 % from 2012 to 2016 (European Commission, Directorate-General for Internal Market, 2021). This disparity highlights a significant imbalance between its metal consumption and investment in exploration. Addressing this gap, a key recommendation for the European Commission is the creation of a funding mechanism, potentially through private–public partnerships or specialized financial mechanisms such as financial vehicles, to stimulate greater investments in these essential projects. Moreover, transparency in environmental and social risks should be paramount in shaping supply chains for minerals essential to the EU's energy transition, ensuring a truly sustainable Green Deal rather than just focusing on supply risk. The 2022 EU Corporate Sustainability Due Diligence Directive (CSDD) seeks to enhance supply chain transparency and sustainability (European Commission, 2022). However, it overlooks small, medium, and micro enterprises (SMEs), which make up 97 % of EU businesses and are fundamental to the European economy. These SMEs, being the backbone of the economy and representing 99 % of all companies in the EU (Kutzschbach et al., 2021), are excluded from the directive, which only applies to larger businesses. In the context of mining, omitting certain high-risk minerals based on the size of their EU consumer base is flawed. Minerals can have major environmental and social impacts even when consumed in small quantities, and supply risks vary widely across minerals. Legislation tailored to individual assessments would thus be more effective and is hence advocated.

#### 5.4.2. *An equally important lever of action: The EU consumption of critical minerals*

By 2040, the consumption of critical material for clean energy, like gallium, lithium, and graphite, is expected to double. This underscores the urgency for the EU to activate diverse strategies to promote sustainable consumption of minerals and metals and further develop resilient value chains. Lowering supply and socio-environmental risks involves decreasing consumption. The EU's current strategy to curb the demand for minerals from primary sources hinges on four main pillars: reusing, recycling, reducing, and reindustrializing minerals.

Reusing and recycling principles via circular economy are integral to the strategies for the first two pillars (Månberger and Stenqvist, 2018; Watari et al., 2020, 2018). For recycling, the EU has set quantified goals as CRMA mandates at least 25 % of the EU's annual consumption of critical raw materials to come from domestic recycling (European Commission, 2023b). Though there have been advancements under the Circular Economy Action Plan (CEAP) (Regueiro and Alonso-Jimenez, 2021), there is a pressing need to further develop them to attain those ambitious recycling rates.

Other development to strengthen the EU's current strategy require research and development activities for emerging technologies, such as direct lithium extraction and enhanced metal recovery to boost future supply volumes, especially for batteries (IEA, 2021a). However, this would require new recycling infrastructures and innovative product design, which follows design-for-disassembly principles, design-for-repair, and design-for-recycling mining minerals (Metabolic and Polaris, 2021) as current design practices prevent mining minerals' reduction, reuse, and recycling (Babbitt et al., 2021). Policymakers should engage relevant parties to tighten EU guidelines, including environmentally friendly design guidelines for batteries.

#### 5.4.3. *One-size-fits-all policy: The solution trap*

Addressing the issue of critical minerals requires specific, adaptable solutions tailored to each unique situation. It is essential to balance local needs with global considerations, ensuring that each unique mining challenge is addressed in a manner that is both effective and contextually appropriate. This approach necessitates a careful consideration of the diverse problems associated with critical minerals, emphasizing the need for targeted and nuanced strategies. This applies to both environmental and social impacts.

For instance, the findings regarding environmental impacts (Figs. 3 and 4) show that few environmental hotspots are concentrating a large part of global environmental impacts. The critical need to identify key players in each hotspot, combined with the reality that certain countries may significantly affect one environmental aspect but not another, underscores the importance of crafting regulations that are specifically targeted at these hotspots. Such tailored regulations are crucial because a broad, one-size-fits-all policy approach might be inefficient or inapplicable to key countries, undermining the overall effectiveness of environmental management strategies.

This need for targeted regulations is even more obvious when considering social issues like modern slavery, ASM and the protection of the most vulnerable. The DRC appears as a hotspot in our results regarding those issues (Fig. 5), and the situation in this country exemplifies the need for localized solutions. Sovacool's extensive fieldwork (2019, 2021) about the ASM in DRC sheds light on the precarious working conditions, inadequate safety measures, and significant health risks. However, he also depicts a complex situation as these challenges exist alongside notable contributions from ASM to poverty reduction, community development, and regional stability (Sovacool, 2019). This research promotes the need for greater transparency in mineral supply chains but also emphasizes the importance of understanding ground realities. It highlights the challenges involved in implementing certification and traceability schemes within ASM, cautioning against the risk of these schemes being reduced to mere public relations tools (Sovacool, 2019). This underlines the need for solutions beyond simplistic approaches, such as the EU imposing a blanket ban on ASM minerals, which could, in some countries, inadvertently cause more harm than good. Instead, in the case of DRC, Sovacool recommends pragmatic approaches including: enforcing safety standards but, more importantly, enforcing the local ability to perform controls on the existing ones, forming joint ventures between ASM and LSM rather than opposing LSM and ASM, promoting fair economic distribution, and supporting alternative livelihoods for people that have no alternative choice than ASM.

More generally, in the case of the DRC and other developing countries facing similar challenges, the EU's direct influence on these issues may be more limited than that of national governments. However, the EU bears responsibility for responding innovatively to those issues. Such a response could involve forming strategic partnerships with those countries, including targeted foreign aid to enhance alternative livelihoods, increase school enrolment near mining sites, and support local NGOs. The challenge here for the EU is to design innovative solutions that carefully balance avoiding political interference while not hindering economic development, ensuring that the exploitation of local resources does not come at the expense of the most vulnerable – the ASM miners, women, and children in the case of the cobalt in mining regions of the DRC (Sovacool, 2021). Lastly, the tailored solutions described above should not prevent the EU from considering top-down approaches inspired by global best practices. Canada's successful implementation of Impact-Benefit Agreements (IBAs) in mining, particularly near indigenous communities, offers a model (O'Reilly and Eacott, 1999). IBAs ensure local benefits like employment, revenue sharing, and environmental protection. For relevant cases, the EU could leverage this model to design and implement best practice criteria, specifically focusing on the establishment of sustainability standards within the selection criteria for its mineral supply chains.

## 6. Conclusion and recommendations

This research highlights the urgent need for a comprehensive, multidimensional approach to address the far-reaching global social and environmental ramifications associated with the European Green Deal's energy transition. Our analysis reveals acute environmental and social challenges at the initial stages of clean energy supply chains, including rising GHG emissions, increased water withdrawal, and heightened risks of forced labor. Therefore, it becomes crucial for the EU, as well as other jurisdictions with ambitious energy policies, to adopt a consumption-focused perspective that thoroughly assesses the multi-faceted risks tied to the sourcing and utilization of critical minerals. The success of energy transition initiatives, both within the EU and globally, fundamentally depends on this more nuanced and inclusive understanding.

For a fair transition, the EU should increase investment in mineral exploration projects, address social concerns often captured by the "NIMBY" (or Not-in-My-Backyard) (Menegaki and Kaliampakos, 2014) EU sentiment towards mining activities, develop circular economy paradigms for critical minerals, intensify research and development initiatives that aim at reducing its external dependence on critical minerals and modernizing its mining sector.

Collaborative efforts from all stakeholders are essential, particularly for protecting vulnerable groups. In areas where the EU's energy transition will impact jobs and well-being, urgent and innovative strategies are required. The EU's approach should involve strategic partnerships, providing targeted aid, while balancing non-interference, economic growth, and the protection of vulnerable populations in mining regions. Tailoring these strategies to each unique situation is critical to avoid a generic "one-size-fits-all" solution that might be inefficient or inapplicable to key countries.

The concept of the "decarbonization divide" is pivotal in scrutinizing the ethical complexities of global decarbonization efforts (Sovacool et al., 2020). It calls for a "whole systems" approach that accounts for far-reaching impacts, beyond immediate technological benefits. Neglecting this divide risks exacerbating vulnerabilities and undermining the objective of a "just transition" that is globally equitable (Markkanen and Anger-Kraavi, 2019). While this study's methodological advancements don't fully operationalize the "decarbonization divide", they do fill some gaps, enabling quantitative analyses of its various facets (Sovacool et al., 2020). Future research should widen its lens to include demands and impacts across different regions and diverse clean energy technologies. Such an approach will furnish policymakers with nuanced, actionable data for crafting targeted policies that address large-scale environmental and social challenges. Additionally, the development and refinement of the methodology proposed in this work will be essential to continue to measure some of the social impacts of the large-scale transition to a low-carbon economy, influencing economic and health inequalities, social cohesion, and well-being that could only be speculated until now (Markkanen and Anger-Kraavi, 2019).

Overall, the EU must embrace its political and institutional role by taking the lead in addressing global social and environmental issues while pursuing its goal of limiting global warming. The negative spillovers of the energy transition should not be ignored, and the EU must take a comprehensive approach to address the significant issues related to the energy transition.

## 7. Data and materials availability

All data and materials used in the analysis are available in the Supplementary Information (SI) and Research Data (RD).

- Supplementary information S1
  - o Figures S1 to S7
  - o Tables S1 to S8
- Supplementary information S2
  - o Data used for the calculation for the figures 2–6, S2-S3, S6 and the tables 2–3, S1, S7.
- Supplementary information S3
  - o Data used for calculating the EU mineral demand.
- Research Data R1
  - o Code and tables used for calculating the detailed mining workforce.

## Funding information

This work is primarily funded through public funding from the Technical University of Denmark.

## CRediT authorship contribution statement

**Etienne Berthet:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Julien Lavalley:** Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Candy Anquetil-Deck:** Formal analysis, Investigation, Software, Writing – original draft, Writing – review & editing. **Fernanda Ballesteros:** Formal analysis, Writing – original draft, Writing – review & editing. **Konstantin Stadler:** Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Ugur Soytas:** Writing – original draft, Writing – review & editing. **Michael Hauschild:** Writing – original draft, Writing – review & editing. **Alexis Laurent:** Conceptualization, Investigation, Project administration, Validation, Writing – original draft, Writing – review & editing.

## 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 extend our heartfelt gratitude to those who contributed to this research. Special thanks are extended to Dr Beatriz Velazquez for bringing to our attention the latest European Commission work on the EU's trade balance of critical raw materials. Her timely contribution provided an invaluable framework for comparing our findings and enriched the depth of our study.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2024.102841.

## References

Azadi, M., Northey, S.A., Ali, S.H., Edraki, M., 2020. Transparency on greenhouse gas emissions from mining to enable climate change mitigation. Nat. Geosci. 13, 100–104. https://doi.org/10.1038/s41561-020-0531-3.

Azapagic, A., 2004. Developing a framework for sustainable development indicators for the mining and minerals industry. J. Clean. Prod. 12, 639–662. https://doi.org/10.1016/S0959-6526(03)00075-1.

Babbitt, C.W., Althaf, S., Cruz Rios, F., Bilec, M.M., Graedel, T.E., 2021. The role of design in circular economy solutions for critical materials. One Earth 4, 353–362. https://doi.org/10.1016/j.oneear.2021.02.014.

Balaram, V., 2019. Rare earth elements: a review of applications, occurrence, exploration, analysis, recycling, and environmental impact. Geosci. Front. 10, 1285–1303. https://doi.org/10.1016/j.gsf.2018.12.005.

Bales, K., Sovacool, B.K., 2021. From forests to factories: how modern slavery deepens the crisis of climate change. Energy Res. Soc. Sci. 77, 102096 https://doi.org/10.1016/j.erss.2021.102096.

Basov, V., 2017. The world's top 10 highest-grade copper mines [WWW document]. COM, MINING https://www.mining.com/the-worlds-top-10-highest-grade-copper-mines/ (accessed 08.01.24).

Baumann-Pauly, D., 2020. Making Mining Safe and Fair: Artisanal cobalt extraction in the Democratic Republic of the Congo. http://www3.weforum.org/docs/WEF_Making_Mining_Safe_2020.pdf (accessed 31.01.24).

Benoît, C., Norris, G.A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., Prakash, S., Ugaya, C., Beck, T., 2010. The guidelines for social life cycle assessment of products: just in time! Int. J. Life Cycle Assess. 15, 156–163. https://doi.org/10.1007/s11367-009-0147-8.

Berthet, E., Anquetil-Deck, C., Stadler, K., et al., 2024. Towards reliable national social footprints: refining work-related injury and fatality metrics. Discov Sustain 5, 47. https://doi.org/10.1007/s43621-024-00185-7.

Bleiwas, D.I., 2010. Byproduct mineral commodities used for the production of photovoltaic cells. https://pubs.usgs.gov/circ/1365/Circ1365.pdf (accessed 31.01.24).

Blengini, G.A., Nuss, P., Dewulf, J., Nita, V., Talens Peiró, L., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., Van Maercke, A., Solar, S., Grohol, M., Ciupagea, C., 2017. EU methodology for critical raw materials assessment: policy needs and proposed solutions for incremental improvements. Resour. Policy 53, 12–19. https://doi.org/10.1016/j.resourpol.2017.05.008.

Buxton, A., 2013. Responding to the challenge of artisanal and small-scale mining. How can knowledge networks help?, International Institute for Environment and Development. https://www.iied.org/16532iied (accessed 31.01.24).

Calvo, G., Mudd, G., Valero, A., Valero, A., 2016. Decreasing ore grades in global metallic mining: a theoretical issue or a global reality? Resources 5, 1–14. https://doi.org/10.3390/resources5040036.

National Minerals Information Center, 2023. Rare Earths Statistics and Information [WWW Document]. U.S. Geol. Surv. URL https://www.usgs.gov/centers/national-minerals-information-center/rare-earths-statistics-and-information (accessed 1.8.24).

Černý, I., Vaněk, M., Maruszewska, E.W., Beneš, F., 2021. How economic indicators impact the EU internal demand for critical raw materials. Resour. Policy 74. https://doi.org/10.1016/j.resourpol.2021.102417.
Chaves, C., Pereira, E., Ferreira, P., Dias, A.G., 2021. Concerns about lithium extraction: a review and application for Portugal. Extr. Ind. Soc. 8, 100928 https://doi.org/10.1016/j.exis.2021.100928.
Ciacci, L., Fishman, T., Elshkaki, A., Graedel, T.E., Vassura, I., Passarini, F., 2020. Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28. Glob. Environ. Chang. 63, 102093 https://doi.org/10.1016/j.gloenvcha.2020.102093.
Commission, E., 2021a. European climate law. Off. J. Eur. Union 2021, 17.
Commission, E., 2023a. Study on the critical raw materials for the EU 2023 final report. European Commission. https://doi.org/10.2873/725585.
Critical Raw Materials Alliance. https://www.crmalliance.eu/hafnium (accessed 31.01.24).
Deblonde, G.J.P., Weigel, V., Bellier, Q., Houdard, R., Delvallée, F., Bélair, S., Beltrami, D., 2016. Selective recovery of niobium and tantalum from low-grade concentrates using a simple and fluoride-free process. Sep. Purif. Technol. 162, 180–187. https://doi.org/10.1016/j.seppur.2016.02.025.
Dehaine, Q., Tijsseling, L.T., Glass, H.J., Törmänen, T., Butcher, A.R., 2021. Geometallurgy of cobalt ores: a review. Miner. Eng. 160, 106656 https://doi.org/10.1016/j.mineng.2020.106656.
Environmental Law Alliance Worldwide (ELAW), 2010. Guidebook for evaluating mining project EIAs, environmental law Alliance worldwide. accessed 31.01.24. https://elaw.org/resource/guidebook-evaluating-mining-project-eias.
Eurometaux, 2019. Metals for a climate neutral Europe: a 2050 blueprint. accessed 31.01.24. https://www.eurometaux.eu/media/1997/exec-summary-metals-2050.pdf.
European Commission, 2008. Communication from the Commission to the European Parliament and the Council. The materials raws initiative — meeting our critical needs for growth and jobs in Europe.
European Commission, 2014. Report on critical raw materials for the EU, Report of the Ad hoc Working Group on defining critical raw materials 41.
European Commission, 2019. The European Green Deal.
European Commission, 2020. Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability.
European Commission, 2021b. Fit for 55 - Delivering the EU's 2030 climate target on the way to climate neutrality. European Commission 15.
European Commission, 2022. Proposal for a directive of the European Parliament and of the Council on Corporate Sustainability Due Diligence and amending Directive (EU) 2019/1937.
European Commission, 2023b. Proposal for a regulation of the European Parliament and of the Council, establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020.
European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2021. 3rd Raw Materials Scoreboard: European innovation partnership on raw materials, Publications Office. https://data.europa.eu/doi/10.2873/567799.
Faber, B., Krause, B., de la Sierra, R.S., 2017. Artisanal mining, livelihoods, and child labor in the cobalt supply chain of the Democratic Republic of Congo. Center for Effective Global Action Policy Report.
Farooki, M., Hinde, C., Lof, A., 2018. Supporting the EU Mineral Sector. Capitalising on EU strengths through an investment promotion strategy. 32.
França Pimenta, A.A., Demajorovic, J., Saraiva de Souza, M.T., de Carvalho Pedro, S., Pisano, V., 2021. Social licence to operate model: critical factors of social acceptance of mining in the brazilian Amazon. Resour. Policy 74, 102237. https://doi.org/10.1016/j.resourpol.2021.102237.
Franks, D., 2012. Social impact assessment of resource projects international mining for development centre mining for development: guide to Australian. Practice 16.
Geng, R., Lam, K.-S., Stevenson, M., 2022. Addressing modern slavery in supply chains: an awareness-motivation-capability perspective. Int. J. Oper. Prod. Manag. 42 (3), 331–356. https://doi.org/10.1108/ijopm-07-2021-0425.
Gielen, D., 2021. Critical minerals for the energy transition. Abu Dhabi.
Giljum, S., Wieland, H., Lutter, S., Bruckner, M., Wood, R., Tukker, A., Stadler, K., 2016. Identifying priority areas for European resource policies: a MRIO-based material footprint assessment. Journal of Economic Structures 5 (1), 17. https://doi.org/10.1186/s40008-016-0048-5.
Gold, S., Trautrims, A., Trodd, Z., 2015. Modern slavery challenges to supply chain management. Supply Chain Management: An International Journal 20 (5), 485–494. https://doi.org/10.1108/SCM-02-2015-0046.
Goldfarb, R., 2015. Tellurium: providing a bright future for solar energy. Reston, VA, USA. .
Gyamfi, E., Appiah-Adjei, E.K., Adjei, K.A., 2019. Potential heavy metal pollution of soil and water resources from artisanal mining in kokoteasua. Ghana. Groundw. Sustain. Dev. 8, 450–456. https://doi.org/10.1016/J.GSD.2019.01.007.
Hajkowicz, S.A., Heyenga, S., Moffat, K., 2011. The relationship between mining and socio-economic well being in Australia's regions. Resour. Policy 36, 30–38. https://doi.org/10.1016/j.resourpol.2010.08.007.
Han, Z., Golev, A., Edraki, M., 2021. A review of tungsten resources and potential extraction from mine waste. Minerals 11. https://doi.org/10.3390/min11070701.
Hetherington, L., Bloodworth, A., 2010. Industrial minerals production in Europe : current situation and future trends. Statistics (Ber) 2007.
Hofmann, M., Hofmann, H., Hagelüken, C., Hool, A., 2018. Critical raw materials: a perspective from the materials science community. Sustain. Mater. Technol. 17, e00074.
IEA, 2020. World Energy Outlook 2020.
IEA, 2021a. The Role of Critical Minerals in Clean Energy Transitions.
IEA, 2021b. Net Zero by 2050: A Roadmap for the Global Energy Sector.
IRENA, 2021. World energy transitions outlook: 1.5 degrees pathway, International Renewable Energy Agency, Abu Dhabi.
IRENA, 2023. Geopolitics of the energy transition: Critical materials. International Renewable Energy Agency, Abu Dhabi. https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Jul/IRENA_Geopolitics_energy_transition_critical_materials_2023.pdf?rev=420aeb58d2e745d79f1b564ea89ef9f8 (accessed 31.01.24).
Ivanova, D., Stadler, K., Steen-Olsen, K., Wood, R., Vita, G., Tukker, A., Hertwich, E.G., 2016. Environmental impact assessment of household consumption. J. Ind. Ecol. 20, 526–536. https://doi.org/10.1111/jiec.12371.
Jara, A.D., Betemariam, A., Woldetinsae, G., Kim, J.Y., 2019. Purification, application and current market trend of natural graphite: a review. Int. J. Min. Sci. Technol. 29, 671–689. https://doi.org/10.1016/J.IJMST.2019.04.003.
Jiang, S., Zhang, L., Li, F., Hua, H., Liu, X., Yuan, Z., Wu, H., 2020. Environmental impacts of lithium production showing the importance of primary data of upstream process in life-cycle assessment. J. Environ. Manage. 262, 110253 https://doi.org/10.1016/j.jenvman.2020.110253.
Koleli, N., Demir, A., 2016. Chapter 11 - Chromite. Environ. Mater. Waste. .
Kutzschbach, J., Tanikulova, P., Lueg, R., 2021. The role of top managers in implementing corporate sustainability—a systematic literature review on small and medium-sized enterprises. Adm. Sci. 11, 44. https://doi.org/10.3390/admsci11020044.
Landrigan, P., Bose-O'Reilly, S., Elbel, J., Nordberg, G., Lucchini, R., Bartrem, C., Grandjean, P., Mergler, D., Moyo, D., Nemery, B., von Braun, M., Nowak, D., 2022. Reducing disease and death from artisanal and small-scale mining (ASM) - the urgent need for responsible mining in the context of growing global demand for minerals and metals for climate change mitigation. Environ. Health 21, 1–13. https://doi.org/10.1186/s12940-022-00877-5.
Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013. Building Eora: a global multi-region input–output database at high country and sector resolution. Econ. Syst. Res. 25, 20–49. https://doi.org/10.1080/09535314.2013.769938.
Leontief, W., 1970. Environmental repercussions and the economic structure: an input-output approach. Rev. Econ. Stat. 52, 262–271. https://doi.org/10.4324/9781315197715-18.
Liu, W., Agusdinata, D.B., 2020. Interdependencies of lithium mining and communities sustainability in Salar de Atacama. Chile. J Clean Prod 260, 120838. https://doi.org/10.1016/j.jclepro.2020.120838.
Liu, W., Agusdinata, D.B., Myint, S.W., 2019. Spatiotemporal patterns of lithium mining and environmental degradation in the Atacama salt flat, Chile. Int. J. Appl. Earth Obs. Geoinf. 80, 145–156. https://doi.org/10.1016/j.jag.2019.04.016.
Løvik, A.N., Hagelüken, C., Wäger, P., 2018. Improving supply security of critical metals: current developments and research in the EU. Sustain. Mater. Technol. 15, 9–18. https://doi.org/10.1016/j.susmat.2018.01.003.
Lu, F., Xiao, T., Lin, J., Ning, Z., Long, Q., Xiao, L., Huang, F., Wang, W., Xiao, Q., Lan, X., Chen, H., 2017. Resources and extraction of gallium: a review. Hydrometall. 174, 105–115. https://doi.org/10.1016/j.hydromet.2017.10.010.
Malik, A., Lafortune, G., Mora, C.J., Carter, S., Lenzen, M., 2022. International in the EU ' s supply chains spillovers embodied.
Månberger, A., Stenqvist, B., 2018. Global metal flows in the renewable energy transition: exploring the effects of substitutes, technological mix and development. Energy Policy 119, 226–241. https://doi.org/10.1016/j.enpol.2018.04.056.
Mancini, L., Sala, S., 2018. Social impact assessment in the mining sector: review and comparison of indicators frameworks. Resour. Policy 57, 98–111. https://doi.org/10.1016/j.resourpol.2018.02.002.
Mancini, L., Benini, L., Sala, S., 2018. Characterization of raw materials based on supply risk indicators for Europe. Int. J. Life Cycle Assess. 23, 726–738. https://doi.org/10.1007/s11367-016-1137-2.
Markkanen, S., Anger-Kraavi, A., 2019. Social impacts of climate change mitigation policies and their implications for inequality. Clim. Pol. 19, 827–844. https://doi.org/10.1080/14693062.2019.1596873.
Marx, J., Schreiber, A., Zapp, P., Walachowicz, F., 2018. Comparative life cycle assessment of NdFeB permanent magnet production from different rare earth deposits. ACS Sustain. Chem. Eng. 6, 5858–5867. https://doi.org/10.1021/acssuschemeng.7b04165.
Meehan, J., Pinnington, B.D., 2021. Modern slavery in supply chains: insights through strategic ambiguity. Int. J. Oper. Prod. Manag. 41 (2), 77–101. https://doi.org/10.1108/IJOPM-05-2020-0292.
Meißner, S., 2021. The impact of metal mining on global water stress and regional Carrying capacities—a GIS-based water impact assessment. Resources 10, 120. https://doi.org/10.3390/resources10120120.
Menegaki, M., Kaliampakos, D., 2014. Mine planning and equipment selection. Mine Planning and Equipment Selection 1437–1446. https://doi.org/10.1007/978-3-319-02678-7.
Metabolic, C., Polaris, Q., 2021. Towards a circular energy transition. exploring solutions to mitigate surging demand for critical metals in the energy transition. accessed on 31 January 2024 Available Online. https://www.copper8.com/towards-a-circular-energy-transtion/.
Miller, R.E., Blair, P.D., 2009. Input-output analysis. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511626982.
Moskalyk, R.R., Alfantazi, A.M., 2003. Processing of vanadium: a review. Miner. Eng. 16, 793–805. https://doi.org/10.1016/S0892-6875(03)00213-9.

Mwaura, F., 2019. An audit of environmental impact assessments for mining projects in Kenya. J. S. Afr. Inst. Min. Metall. 119, 485–493. https://doi.org/10.17159/24119717/143/2019.

Noetstaller, R., Bank, W., Washington, D.C., 1995. Historical perspective and key issues of artisanal mining Keynote speech at the International Roundtable on Artisanal Mining organized by the.

Norris, C., Norris, G., 2015. Chapter 8: The Social Hotspots Database Context of the SHDB.

Norris, C.B., Norris, G., Aulisio, D., 2013. Social Hotspots Database.

O'Reilly, K., Eacott, E., 1999. Aboriginal peoples and impact and benefits agreements: report of a National Workshop. Canadian Arctic Resources Committee, Yellowknife, NT.

Regueiro, M., Alonso-Jimenez, A., 2021. Minerals in the future of Europe. Miner. Econ. 34, 209–224. https://doi.org/10.1007/s13563-021-00254-7.

Reichl, C., Schatz, M., 2021. World Mining Data 2021.

Ruiz, A.G., Sola, P.C., Palmerola, N.M., 2018. Germanium: Current and Novel Recovery Processes, Advanced Material and Device Applications with Germanium. Intech. https://doi.org/10.5772/intechopen.77997.

Sadegh Safarzadeh, M., Bafghi, M.S., Moradkhani, D., Ojaghi Ilkhchi, M., 2007. A review on hydrometallurgical extraction and recovery of cadmium from various resources. Miner. Eng. 20, 211–220. https://doi.org/10.1016/J.MINENG.2006.07.001.

Sen, B., Onat, N.C., Kucukvar, M., Tatari, O., 2019. Material footprint of electric vehicles: a multiregional life cycle assessment. J. Clean. Prod. 209, 1033–1043. https://doi.org/10.1016/j.jclepro.2018.10.309.

Sovacool, B.K., 2019. The precarious political economy of cobalt: balancing prosperity, poverty, and brutality in artisanal and industrial mining in the Democratic Republic of the Congo. Extr. Ind. Soc. 6, 915–939. https://doi.org/10.1016/j.exis.2019.05.018.

Sovacool, B.K., 2021. When subterranean slavery supports sustainability transitions? power, patriarchy, and child labor in artisanal congolese cobalt mining. Extr. Ind. Soc. 8, 271–293. https://doi.org/10.1016/j.exis.2020.11.018.

Sovacool, B.K., Hook, A., Martiskainen, M., Brock, A., Turnheim, B., 2020. The decarbonisation divide: contextualizing landscapes of low-carbon exploitation and toxicity in Africa. Glob. Environ. Chang. 60, 102028 https://doi.org/10.1016/j.gloenvcha.2019.102028.

Spohr, M., 2016. Human rights risks in mining - a baseline study. Max Planck Foundation 6–148.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., de Koning, A., Tukker, A., 2018. EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables. J. Ind. Ecol. 22, 502–515. https://doi.org/10.1111/jiec.12715.

Starke, L., 2016. Breaking new ground: mining, minerals, and sustainable development. Breaking New Ground: Mining, Minerals and Sustainable Development 1–446. https://doi.org/10.4324/9781315541501.

Surianti, Utami, A.N., Permatasari, M.A., Bendiyasa, I.M., Astuti, W., Petrus, H.T.B.M., 2020. Valuable metals precipitation of low grade nickel ore leachate using sodium hydroxide. IOP Conf. Ser. Mater. Sci. Eng. 742. .

Tarras-Wahlberg, N.H., 2002. Environmental management of small-scale and artisanal mining: the portovelo-Zaruma goldmining area, southern Ecuador. J. Environ. Manage. 65, 165–179. https://doi.org/10.1006/jema.2002.0542.

Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., Stadler, K., Wood, R., 2016. Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. Glob. Environ. Chang. 40, 171–181. https://doi.org/10.1016/j.gloenvcha.2016.07.002.

United Nations Environment Programme, 2009. Guidelines for social life cycle assessment of products.

United States Geological Survey, 2021. Mineral Commodity Summaries. https://doi.org/10.3133/mcs2021.

Valero, Alicia, Valero, Antonio, Calvo, G., Ortego, A., 2018. Material bottlenecks in the future development of green technologies. Renew. Sustain. Energy Rev. 93, 178–200. https://doi.org/10.1016/j.rser.2018.05.041.

Van den Berg, J.A.M., Yang, Y., Nauta, H.H.K., Van Sandwijk, A., Reuter, M.A., 2002. Comprehensive processing of low grade sulphidic molybdenum ores. Miner. Eng. 15, 879–883. https://doi.org/10.1016/S0892-6875(02)00135-8.

Wang, C., 2016. Selenium minerals and the recovery of selenium from copper refinery anode slimes. J. South. African Inst. Min. Metall. 116, 593–600. https://doi.org/10.17159/2411-9717/2016/v116n6a16.

Watari, T., McLellan, B.C., Ogata, S., Tezuka, T., 2018. Analysis of potential for critical metal resource constraints in the international energy agency's long-term low-carbon energy scenarios. Minerals 8. https://doi.org/10.3390/min8040156.

Watari, T., Nansai, K., Nakajima, K., 2020. Review of critical metal dynamics to 2050 for 48 elements. Resour. Conserv. Recycl. 155, 104669 https://doi.org/10.1016/j.resconrec.2019.104669.

Wiebe, K.S., Bjelle, E.L., Többen, J., Wood, R., 2018. Implementing exogenous scenarios in a global MRIO model for the estimation of future environmental footprints. Journal of Economic Structures 7 (1), 20. https://doi.org/10.1186/s40008-018-0118-y.

Wiedmann, T., 2009. A review of recent multi-region input-output models used for consumption-based emission and resource accounting. Ecol. Econ. 69, 211–222. https://doi.org/10.1016/j.ecolecon.2009.08.026.

Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. PNAS 112, 6271–6276. https://doi.org/10.1073/pnas.1220362110.

Yang, B., He, J., Zhang, G., & Guo, J. (Eds.). (2021). Chapter 3 - Vanadium mineral resources. In Vanadium (pp. 33–58). Elsevier. https://doi.org/10.1016/B978-0-12-818898-9.00003-6.