Three open questions on Net Zero in the mining and metals industries

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Three open questions on Net Zero in the mining and metals industries

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Abstract
The mining and metals industries are facing the conflicting challenges of meeting an anticipated skyrocketing metals demand while drastically decarbonizing and reducing other environmental impacts. Over the past few years, decarbonization has become a key topic within the sector, with global scale initiatives and a massive response from companies. Here, we provide a snapshot of the industry's progress towards decarbonization, building on the most recent research papers, industry reports, and the public corporate documents of twenty major mining and metals companies. The objective is to highlight how the concept of Net Zero (NZ) has been interpreted within the sector and critically discuss the key strategies to achieve it. Today, nearly all the leading companies have set ambitious decarbonization targets, with many aiming to achieve Net Zero operational emissions (Scope 1 and 2) by 2050. According to the proposed decarbonization roadmaps, massive deployment of renewable energy is likely to drive substantial emission reductions in the short-term (before 2030). Instead, long-term decarbonization targets (2050) are expected to be achieved by combining carbon offsets strategies with the implementation of multiple breakthrough technologies, such as battery electric mining trucks, process heat electrification, and green hydrogen. Despite the ambitious goals, sometimes underpinned by clear roadmaps and remarkable investment agendas, three questions remain open and the responses uncertain to various extent: 1. What does NZ mean in practice for the sector? 2. To what extent long term strategies that companies announced are viable and credible? 3. What's the role of Life Cycle Assessment in setting and monitoring Scope 3 reduction targets?

Keywords Net Zero · Mining · Decarbonization · Critical raw materials · Energy transition in the mining sector

Acronyms

BEMTs	Battery Electric Mining Trucks
CCUS	Carbon Capture, Utilization, and Storage
CF	Carbon Footprint
CN	Carbon Neutral
CRMs	Critical Raw Materials
GHG	Greenhouse Gases
HFC	Hydrofluorocarbons
ICA	International Copper Association
ICMM	International Council on Mining and Metals
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LIBs	Lithium-Ion Batteries
MACC	Marginal Abatement Cost Curves
MOE	Molten Oxide Electrolysis
NZ	Net Zero
NZE	Net Zero Emission
PGMs	Platinum Group Metals
PPAs	Power Purchase Agreements
PV	(Solar) Photovoltaics
REE	Rare Earth Elements
RES	Renewable Energy Sources
SM	Supplementary information Material
SPS	Stated Policies Scenario
SSPs	Shared Socio-economic Pathways
UNFCCC	United Nations Framework Convention on Climate Change

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Introduction

Critical Raw Materials in decarbonization strategies and the decarbonization of their supply chains

Global awareness about the consequences of climate change has grown exponentially in recent times, and measures to mitigate it have become central in public and corporate policies at various scales. Today, the global energy system is trying to reduce its reliance on fossil fuels, and renewables are growing at a fast pace, boosted by strong policy support and cost reductions (IEA 2024c). Over the past decade, the proportion of fossil fuels within the global energy mix has gradually declined (by approximately 2%), while global energy demand has risen by 15%, with clean energy sources accounting for 40% of this growth. In 2023 alone, solar photovoltaics (PV) and wind capacities increased, respectively, by 425 GW and 116 GW, and 78 EJ out of 642 EJ of the total energy supply were derived from renewables (IEA 2024a, c). Projections from the International Energy Agency (IEA) suggest that renewable energy consumption should at least further increase by 60% between 2024 and 2030 (IEA 2024b).

Within this ongoing energy transition, the mining and metals industry is playing a pivotal role, due to the strong dependence of clean energy technologies on Critical Raw Materials (CRM) such as lithium, nickel, cobalt, and copper (UNEP 2024). As the world moves to a more electrified and renewables-rich energy system, the demand for these materials is expected to largely increase within the next decades (IEA 2024a). By 2050, the overall mineral demand for clean energy technologies is expected to grow from current levels by approximately 150% under the IEA Stated Policies Scenario (SPS), and by as much as 273% under the IEA Net Zero Emissions scenario (NZE) (see Table 1 for materials-specific projections).

Today, primary mineral and metal production is claimed to be responsible for approximately 10% of the global energy-related greenhouse gas (GHG) emissions (Azadi et al. 2020). This sector is highly carbon-intensive and is characterized by a notable volume of hard-to-abate emissions. This raises concerns about the future GHGs emissions of the whole mining and metals industry, particularly in view of the projected skyrocketing metals demand and the expected decline in ore grades and shift towards more energy-intensive resources (Hodgkinson and Smith 2021). Without effective decarbonization strategies, there is the risk that the mining and metals industry could significantly increase its emissions, as well as other environmental impacts, while supporting a booming metals demand to enable a green energy transition (Harpprecht et al. 2024; Sonter et al. 2020).

Table 1 Current and projected single mineral demand for clean energy technologies under two different IEA scenarios (SPS and NZE) by 2050, with 2023 as reference year (IEA 2024a).

Mineral	Demand [kt]	Projected increase in demand by 2050 by Scenario [%]	
	2023	SPS	NZE
Copper	6371.7	103	202
Cobalt	64.4	235	401
Graphite (battery grade)	772.2	275	510
Lithium	92.1	1031	1609
Manganese	181.7	1025	1579
Nickel	477.7	334	548
PGMs (Iridium excluded)[1]	9.8×10^{-4}	1481	8850
REE[2]	16.3	252	389
Silicon	1126.1	71	120
Tantalum	0.1	351	151
Zinc	731.0	128	146

[1]PGMs: Platinum Group Metals;

[2]REE: Rare Earth Elements.

Van der Voet et al. (2018) emphasized that a steeply rising demand, coupled with declining ore grades, is expected to drive substantial increases in the environmental impacts associated with global metals production. Their analysis suggested that a global shift to renewable electricity coupled only with efficiency improvements within the mining sector will not be sufficient to achieve an absolute decoupling between metal consumption and environmental impacts. Similarly, Yokoi et al. (2022) showed that without the implementation of breakthrough technologies, future GHG emissions from metals production will not align with the climate targets required to keep global temperature rise below 2°C under any of the shared socio-economic pathways (SSPs). Moreover, as highlighted by Watari wt al. (2022), even more ambitious decarbonization strategies might not be sufficient to offset the effects of a skyrocketing demand and to achieve emissions reductions in line with a 1.5°C climate target. These findings underscored the need for developing aggressive decarbonization strategies for counterbalancing the potential negative effects of a future skyrocketing metals demand.

In response to these increasing concerns, the attention towards decarbonization within the mining and metals sector has grown exponentially in recent years, driving concrete emission reduction strategies and boosting research on the topic. In 2023, the International Finance Corporation developed a decarbonization roadmap for copper and nickel production, outlining a potential pathway to achieve Net Zero emissions by 2050 (International Finance Corporation 2023). Similarly, Istrate et al. (2024) applied the Life Cycle Assessment (LCA) methodology to quantify the mitigation potential of different decarbonization strategies for primary battery raw materials supply chains, identifying both opportunities and key challenges for achieving substantial emission reductions within these supply chains.

Alongside these efforts, industry-wide initiatives have proliferated, with the term *Net Zero* becoming widely adopted across the whole sector. For instance, in 2021 members of the International Council on Mining and Metals (ICMM) have collectively committed to achieve Net Zero Scope 1 and 2 emissions by 2050 or sooner (ICMM 2021). Similarly, in 2023, Tianqi Lithium invited the main actors in the lithium value chain to achieve Net Zero in their business operations by 2050 through its initiative "Changing the World with Lithium - Net Zero" (Tianqi Lithium 2023). In the same year, members of the International Copper Association (ICA) developed a collective decarbonization roadmap for bringing the carbon footprint of copper as close as possible to Net Zero by 2050 (ICA 2023).

Interpretation of climate related key-terms

Although decarbonization has now become a central priority across many industrial sectors, there is still no an agreed consensus on the terminology to be used. Terms like *Carbon Neutrality*, *Net Zero emissions*, and related concepts, are frequently adopted in climate policies and voluntary emission reductions commitments, often interchangeably (Green and Reyes 2023). However, despite some similarities, these concepts are grounded in distinct conceptual frameworks and present few notable differences (Van Coppenolle et al. 2022; Chen et al. 2024).

Initially introduced in physical climate science, the origin of terms like Carbon Neutrality or Net Zero can be traced back to the 1992 United Nations Framework Convention on Climate Change (UNFCCC); that moment boosted the emergence of different terms to describe global emissions reduction targets. Among these, Carbon Neutrality was one of the first to gain traction (Green and Reyes 2023). However, following the publication of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC 2014) and the signing of the 2015 Paris Agreement, Net Zero became the dominant term in both climate policies and voluntary emission reduction schemes (Van Coppenolle et al. 2022).

From a physical climate science standpoint, Carbon Neutrality and Net Zero are similar concepts with a few fundamental differences, embodying distinct conceptual frameworks (Van Coppenolle et al. 2022; Chen et al. 2024). First, Carbon Neutrality (in some cases, also indicated as Net Zero CO_2 emissions) refers specifically to a state in which only anthropogenic carbon dioxide emissions are balanced by anthropogenic CO_2 removals. On the other hand, Net Zero extends this concept by addressing the full spectrum of GHGs - e.g., methane, nitrous oxide, hydrofluorocarbons (HFCs), etc. - thus representing a condition in which anthropogenic GHG emissions to the atmosphere (converted to an equivalent quantity of CO_2 emissions) are balanced by anthropogenic GHG removals over a specified period (IPCC 2021). Furthermore, while Net Zero is explicitly linked to global climate goals, such as those defined in the Paris Agreement (Fankhauser et al. 2022; Krebbers and Ferguson 2021; National Grid 2022), Carbon Neutrality lacks in such a formalized connection (Rogelj et al. 2021; Allen et al. 2022; Wei et al. 2022).

Since their introduction in physical climate science, the concepts of Net Zero and Carbon Neutrality have been adopted - often interchangeably - to guide voluntary emission reduction initiatives at the corporate level (Fankhauser et al. 2022). In this context, their definition has changed over time, slightly diverging from their IPCC origins (Allen et al. 2022), particularly in terms of implementation strategies and scope range (see Table 2 for corporate emissions scopes definitions) (Van Coppenolle et al. 2022; Chen et al. 2024). Specifically, at the corporate level, Carbon Neutrality typically does not require reducing absolute emissions, but

Table 2 Definitions of emissions scopes in corporate reporting, based on the Greenhouse Gas Protocol (WRI, WBCSD 2004).

Scope	Definition	Source
Scope 1	Direct GHG emissions from sources that are owned or controlled by the company (typically occurring on-site).	WRI, WBCSD (2004)
Scope 2	Indirect GHG emissions from purchased electricity, steam, heat and cooling.	WRI, WBCSD (2004)
Scope 3	Indirect emissions from a company's upstream and downstream activities (including all the value chain). They derive from activities related to assets not owned or controlled by the reporting entity, but that the organization indirectly impacts in its value chain: they enclose all emission sources outside the entity's Scope 1 and Scope 2 boundaries (value chain emissions). Scope 3 emissions often represent the largest part of an organization's total GHG emissions.	WRI, WBCSD (2004), EPA (2025)

rather focuses on achieving a balance between emissions and offsets. This approach generally covers only Scope 1 and Scope 2 emissions, while Scope 3 emissions are usually disregarded or encouraged for possible consideration. Krebbers and Ferguson (2021). By contrast, Net Zero includes all emissions scopes and requires reducing emissions as close to zero as possible, limiting the reliance on carbon offsets to the most hard-to-abate emissions (Krebbers and Ferguson 2021; National Grid 2022; Schneider Electric 2022; S&P Global 2024). As a result, voluntary Net Zero commitments are generally seen as more ambitious, setting stricter limits on the use of offsets and requiring a more comprehensive approach in which value and supply chains are accountable for mitigating their associated GHG emissions.

Within this framework, the Life Cycle Assessment (LCA) methodology can represent a valuable tool for supporting such claims, allowing to assess potential emissions along entire supply chains (Sadhukhan 2022; Tamoor et al. 2023), from upstream material sourcing to downstream product disposal (from cradle-to-grave) (Karlsson et al. 2020; Sen et al. 2023). Moreover, LCA may support in verifying the effectiveness of the measures considered by a company, and may also support considering broader impact categories besides GHG emissions (Chen et al. 2024).

The aim and the structure of this paper

This study provides a snapshot of the industry's progress towards decarbonization, building on the most recent publications on the topic, including research papers, industry reports, and the public corporate documents of twenty major mining and metals companies. The objective and the novelty of this work are to highlight how the concept of Net Zero has been interpreted within the mining and metals sector and to critically analyze the main strategies proposed to achieve it. Moreover, we highlight and discuss three critical open questions related to existing decarbonization roadmaps:

1. What does Net Zero mean in practice for the mining and metals industries and what constitutes an acceptable level of offsets?
2. To what extent long-term strategies that companies announced are viable and credible?
3. What's the role of Life Cycle Assessment in setting and monitoring Scope 3 reduction targets?

Addressing these questions will be essential for aligning the industry's efforts towards a unified direction and overcoming the remaining barriers towards achieving Net Zero.

This paper is structured as follows: Section"Data and methods" outlines the documentation reviewed and the methodological approach adopted for this assessment; Section"Results" provides an overview of current decarbonization efforts within the mining and metals industry, highlighting the main features of the proposed targets and strategies; Section"Discussion" discusses three key open questions associated with existing decarbonization roadmaps, identifying critical barriers that might hinder the sector's ability to drastically reduce its emissions; Section"Conclusions" provides concluding remarks and proposes potential answers to the open questions identified.

Data and methods

To provide an in-depth overview of the industry's progress towards decarbonization, we analyzed the decarbonization roadmaps proposed by twenty of the leading mining and metals companies. These were selected considering the highest 2023 production volumes reported by S&P Global (S&P Global 2024), with the only exclusion of companies whose main source of income was represented by coal. The final twenty companies selected within the study - summarised in Table 3 - represent the major global producers of copper, iron ores, nickel, lithium, cobalt, and other critical commodities. As global diversified commodities producers, these companies are subject to high public and consumer scrutiny regarding their environmental performance, which places them under significant pressure to set ambitious decarbonization targets and implement effective mitigation solutions. Therefore, an analysis of their decarbonization strategies was deemed appropriate for providing a representative and comprehensive overview of the progress towards decarbonization of the whole sector. However, it should be highlighted that, rather than comparing these companies' decarbonization roadmaps, the aim of this analysis is only to provide a snapshot of the current state of the industry at this time and explore how key players in the mining and metals sector are advancing towards decarbonization.

For each of the companies selected we gathered the latest publicly available corporate documents on the topics of decarbonization and sustainability. The priority was given to the most recent reports on decarbonization strategies (e.g., Climate Change Reports, Climate Change Action Plans, Climate Action Transition Plans), when available. In the case such specific information could not be found, the latest Sustainability Reports were selected. Lastly, when the sources analyzed were not considered sufficient for obtaining a detailed understanding of a company's decarbonization strategy, additional reports were assessed, including the latest annual Integrated Reports and other documents on sustainability aspects available on the

Table 3 List of the companies selected for this assessment and their respective core commodities. Bold characters indicate that the company was one of the main global producers of that specific commodity in 2023.

Company	Main commodities produced
Agnico Eagle Mines	**Gold**, Silver, Zinc, Copper
Albemarle	**Lithium**, Bromine
Anglo American	Copper, Nickel, **PGMs**, Iron ore, Steelmaking coal, **Manganese**
Barrick Gold	**Gold**, Copper and by-products
BHP	**Copper**, **Iron ore**, Steelmaking coal, Nickel, Thermal coal
CMOC group	**Cobalt**, Molybdenum, Copper, **Niobium**
Codelco	**Copper** and by-products (**Molybdenum**, Silver, Gold, Rhenium)
First Quantum Minerals	**Copper**, Nickel, Gold, Zinc, Cobalt
Fortescue	**Iron ore**
Freeport-McMoRan	**Copper**, Gold, **Molybdenum**
Glencore	Copper, **Cobalt**, Nickel, **Zinc**, Aluminium, **Silver**, Thermal coal, Steelmaking coal
KGHM	Copper, Gold, **Silver**, Molybdenum, Rhenium
Newmont	**Gold**, Copper, Silver, Zinc, Lead
Norilsk Nickel	**Nickel**, **PGMs**, Cobalt, Copper
Rio Tinto	**Iron ore**, Aluminium, Copper, Titanium, Lithium, Borates
South32	Aluminium, Copper, Silver, Lead, Zinc, Nickel, **Manganese**
Southern Copper	Copper, **Molybdenum**, Zinc, Silver, Lead, Gold
SQM	**Lithium** and co-products
Vale	**Iron ore**, **Nickel**, Copper, Cobalt, Manganese, PGMs, Gold, Silver
Zijin Mining	Copper, Gold, **Zinc**, Lead, Lithium, PGMs, Molybdenum

companies' websites (e.g., ESG Supporting Documents, Climate Policy documents, Carbon Disclosure Project documents). A full list of the documentation assessed within this study is presented in the Supplementary Material (see SM, Table S1).

Subsequently, to ensure that our analysis captured the ongoing decarbonization efforts within the entire mining and metals industry, we integrated insights from the most recent publications on the topic, including research papers, industry reports, and other grey literature documents. These publications covered a wide range of aspects related to the decarbonization of mining and metallurgical operations, including: the sources of emissions within the whole industry or for specific metals supply chains, the potential technological solutions proposed to mitigate emissions, LCAs of metals, and existing initiatives towards decarbonization proposed by industry associations.

Results

Decarbonization targets in the mining and metals industry

Compared to the early insights from the IEA (IEA 2021), recent global scale initiatives towards decarbonization have led to a massive response from companies within the mining and metals industries.

Today, nearly all major companies in the sector have committed to reducing emissions, setting both short-term and long-term decarbonization targets, with many aiming to achieve Net Zero emissions by 2050 (as reported in Table 4). In particular, Net Zero has emerged as the leading concept in decarbonization strategies, reflecting a long-term objective towards which the industry is increasingly aligning.

Although much of this progress remains at the planning stage, it signals a promising shift – companies are not only prioritizing decarbonization in their strategic agendas but are also beginning to define roadmaps and investing in renewable electricity and breakthrough decarbonization technologies. This shift is particularly promising given the sector's traditionally high dependence on fossil fuels, its carbon-intensive processes, and the hard-to-abate nature of many of its operations.

In the industry, decarbonization targets are primarily defined at the corporate level, based on the concept of Corporate Carbon Footprint as defined by The Greenhouse Gas Protocol (WRI, WBCSD 2004). However, only a limited number of them has been approved by existing standards, largely due to the lack of industry-specific guidelines and the limited applicability of existing Net Zero standards to diversified commodities producers (Kirk and Lund 2018; Anglo American 2024; BHP 2024; Glencore 2024).

These targets are generally separated between operational emissions (Scope 1 and 2), historically the focus of corporate reporting, and indirect value chain emissions (Scope 3). This distinction is motivated by the fact that, while Scope 1 and Scope 2 emissions result from the direct activities of

Table 4 Decarbonization targets set by twenty of the leading companies in the mining and metals industry. Intensity-based targets (e.g., $kg_{CO_{2,eq}}$ per kg of metal produced) are highlighted in bold, while the remaining targets are set at corporate level; brackets indicate [baseline yr]

Emission reduction targets [%]						
	Short-term (2030)		Medium-term (2040)		Long-term (2050)	
	Scope 1 & Scope 2	Scope 3	Scope 1 & Scope 2	Scope 3	Scope 1 & Scope 2	Scope 3
Agnico Eagle Mines	$30_{[2021]}$	–			NZ	–
Albemarle	$\mathbf{35}_{[2019]}$ Except Li	–			NZ	–
Anglo American	$30_{[2016]}$	–	CN	$50_{[2020]}$		
Barrick Gold	$30_{[2018]}$	–			NZ	–
BHP	$30_{[2020]}$	–			NZ	NZ
CMOC Group	$\mathbf{15}_{[2022]}$	–	$38_{[2030]}$[1] $\mathbf{60}_{[2022]}$	–	CN	–
Codelco	$70_{[2019]}$	–			CN	–
First Quantum Minerals	$50_{[2020]}$	–			–	–
Fortescue	NZ	–	–	NZ		
Freeport-McMoRan	$\mathbf{15}^{a}{}_{[2018]}$ $\mathbf{30}^{b}{}_{[2018]}$ $50^{c}{}_{[2018]}$ $35^{d}{}_{[2018]}$	–			NZ	–
Glencore	$25_{[2019]}$	$25_{[2019]}$	$50_{[2019]}{}^{*}$	$50_{[2019]}{}^{*}$	NZ	NZ
KGHM	$30_{[2020]}$	–			CN	–
Newmont	$32_{[2018]}$	$30_{[2019]}$			NZ	–
Norilsk Nickel	–	–			–	–
Rio Tinto	$50_{[2018]}$	–			NZ	NZ
South32	–	–	$50_{[2021]}{}^{*}$	–	NZ	NZ
Southern Copper	$8_{[2018]}{}^{***}$	$10_{[2022]}{}^{***}$	$40_{[2018]}{}^{*}$	$20_{[2022]}{}^{*}$	NZ	$30_{[2022]}$
SQM	$46_{[2021]}{}^{****}$ Li only	$\mathbf{55}_{[2021]}{}^{****}$ Li only	**CN**	–		
Vale	$33_{[2017]}$	–	–	$15_{[2018]}{}^{*}$	NZ	–
Zijin Mining	$\mathbf{38}_{[2020]}{}^{**}$	–			CN	–

NZ: Net Zero; CN: Carbon Neutral;*Target year: 2035;**Target year: 2029;***Target year: 2027;****Target year: 2031.Relative to:^{a}Copper operations in North and South America;^{b}Operations in Indonesia;^{c}Copper smelting and refining operations;^{d}Molybdenum operations;

[1]Target referred to the emission peak expected to be reached in 2030

the reporting company and are thus easier to measure and manage, Scope 3 emissions arise from the activities of other value chain actors, and are outside the direct control of the reporting company. This makes them very challenging to estimate and control (ICMM 2021, 2023).

Fig. 1 reports the annual emissions of the companies considered, separated by scope. For operational emissions, Scope 1 values are in most cases higher than Scope 2 emissions linked to electricity consumption, underlining the potential challenges of significantly reducing emissions within the sector. Scope 3 emissions (upstream and downstream), however, are far from negligible: in many cases they are comparable to, or even exceed, the sum of operational emissions (see SM, Tables S2 and S3). Their distribution reflects the structure of companies' portfolios. Large producers of iron ore, energy commodities, or other intermediate metallic compounds show particularly high downstream Scope 3 emissions from the processing and use of sold products (companies positioned on the right side of the figure). In contrast, for other producers (companies on the left side of the figure), Scope 3 emissions are mostly linked to upstream categories (for detailed information see SM, Fig. S1), such as the production of fuels or reagents consumed in operations. Such emissions, range between 15%–71% of companies cradle-to-gate emissions (Scope 1 + 2 + 3-upstream).

It is important to note that Scope 3 reporting in the industry is still at an early stage, with many companies covering only part of the fifteen categories set out in the Greenhouse Gas Protocol (see SM, Table S3), and sector-specific guidance only released by the ICMM in 2023 (ICMM 2023). Consequently, while companies have intensified their Scope 3 emissions reporting, the decarbonization roadmaps proposed within the industry still often lack of specific targets for Scope 3 emissions. Moreover, while these roadmaps tend to feature clear and detailed strategies for addressing operational emissions, they are less specific about what concerns value chain emissions.

Strategies to reduce operational emissions

To meet its targets, the mining and metals industry is exploring a diverse range of strategies to reduce operational emissions. Some of these solutions are already available at scales and implemented in real-life operations, while others are only being tested at smaller scales and are expected to become technologically and commercially mature only in the coming years. Table 5 provides a fairly comprehensive overview for some of the key aspects of the strategies proposed within the decarbonization roadmaps assessed in this study, highlighting their current level of development, potential costs, timeline of implementation, and emission reduction potential. While providing a qualitative assessment, the information presented by the authors of this study combine insights from current scientific literature, industry reports, and corporate strategies, offering a comprehensive overview of the strategies proposed to substantially reduce operational emissions within the sector. A detailed explanation of the methodology adopted for this qualitative assessment has been reported in the Supplementary Material (SM).

Depending on their current level of technological and commercial maturity, the proposed decarbonization solutions are expected to contribute to mitigation efforts in three different periods: short-term (now to 2030), medium-term (2030 to 2040), or long-term (2040 to 2050). In the short-term, existing decarbonization roadmaps primarily rely on increased operational and energy efficiency and massive deployment of renewable energy. These solutions are currently the most cost-effective and technologically mature, while also potentially enabling significant emission reductions (International Finance Corporation 2023). In this period, the transition to renewable electricity is expected to occur largely through Power Purchase Agreements (PPAs), while on-site renewable systems are mostly being considered for off-grid operations. PPAs are generally preferred because

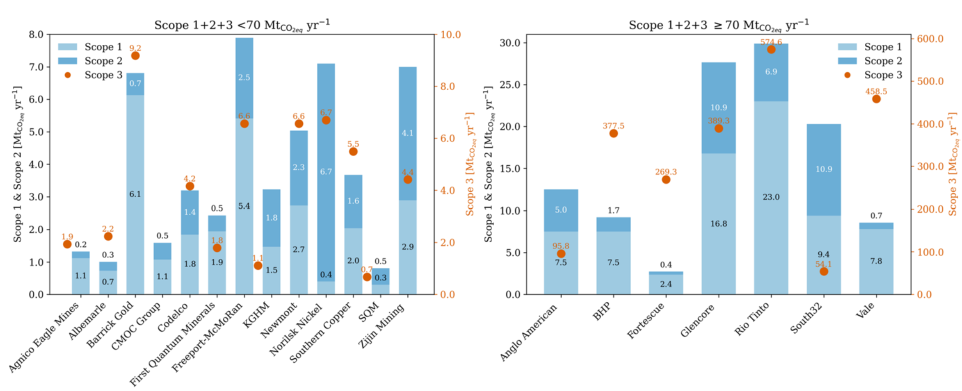

Fig. 1 Annual emissions of the companies assessed in this study, separated by scope. Stacked bars represent operational emissions (Scope 1 and 2), while dots indicate Scope 3 emissions (scaled on the right axis). For readability, companies are divided according to whether their total annual emissions (Scope 1 + 2 + 3) exceed 70 $Mt_{CO_{2,eq}}$

Table 5 Main features of the technological solutions proposed to reduce operational emissions in the mining and metals industries.

Innovations in the mining & metals industries	Expected implementation at scales	Current level of development	Potential investment required	Decarbonization potential
Efficiency improvements				
Equipment efficiency	Short-term	■■■	■□□	■□□
Energy efficiency	Short-term	■■■	■□□	■□□
Process optimisation	Short-term	■■■	■□□	■□□
Renewable energy				
PPAs	Short-term	■■■	■□□	■■■
On-site RES[1]	Short-term	■■■	■■□	■■■
Joint ventures for RES projects	Short-term	■■■	■□□	■■■
Decarbonization of process heat				
Electrification	Mid-term	■■□	■■■	■■■
Green Hydrogen	Long-term	■□□	■■■	■■■
Renewable fuels	Long-term	■□□	■■■	■■□
Electrification of processing equipment	Short-term	■■■	■□□	■□□
Innovative processes	Long-term	■□□	■■■	■■■
CCUS[2]	Long-term	■□□	■■■	■■□
Materials transport innovations				
Electrification of road & railway movement	Mid-term	■■□	■□□	■□□
Innovative fuels for maritime shipping	Long-term	■□□	■■■	■□□
In-mine material movement innovations - Trucks				
BEMTs[3]	Mid-term	■■□	■■□	■■■
Trolley assisted hybrid trucks	Short-term	■■■	■□□	■■□
Green hydrogen-powered trucks	Long-term	■□□	■■■	■■■

[1] RES: Renewable Energy Sources

[2] CCUS: Carbon Capture, Utilization, and Storage

[3] BEMTs: Battery Electric Mining Trucks

they require lower initial capital investments, present fewer technological challenges, offer greater security, and can be used to cover large-scale electricity demands (Hodgkinson and Smith 2021; Enemuo and Ogunmodimu 2025). In many cases, the transition to renewable electricity could drive substantial emission reductions, given the significant contribution of electricity to overall emissions in the sector (Fig. 1) and for several metals production routes (see SM, Table S6).

In the medium-term, additional emissions reductions are expected to be driven by the widespread implementation of battery electric mining trucks and the electrification of process heat. These solutions are essential for addressing residual emissions that cannot be eliminated through the transition to renewable electricity alone, which, in many cases, remain substantial (Fig. 1). Fleet electrification, in particular, has been recognized as a key strategy by all the major players within the mining and metals industry, given the large volumes of emissions associated with conventional diesel-powered mining trucks (The Copper Mark, RMI 2024). While several companies are already introducing battery electric mining vehicles in their operations (Fortescue 2024; South32 2023; Vale 2024), large scale deployment is anticipated only by 2030-2035, with full fleet electrification likely to be achieved from 2040 onwards. Similarly, while many heat electrification solutions are already technologically mature, their large-scale implementation is still hindered by their high operational costs (Wei et al. 2019). As a result, they are expected to contribute to mitigation efforts only from the medium-term onwards.

In the long-term, companies aim to achieve final emission reductions in line with their 2050 targets by implementing multiple breakthrough technologies, that are not yet technologically and commercially viable. Examples include the use of green hydrogen both as a reagent and an energy source, or innovative metallurgical processes like the Molten Oxide Electrolysis (MOE). These technologies are considered essential to reduce a substantial share of the industry's hardest-to-abate emissions, such as direct process emissions.

Given the currently limited level of technological development and economic feasibility of many of the decarbonization solutions proposed, most of the leading companies within sector have not yet developed detailed decarbonization roadmaps beyond 2030. Instead, they only outline the key strategies they aim to implement, with plans of defining their long-term strategies in detail only in the coming years, constantly adjusting them in line with the progress of selected technological solutions. In many cases, the selection of the most effective strategies will be based on internal Marginal Abatement Cost Curves (MACC).

Moreover, despite the promising nature of most of the decarbonization solutions, mining and metals companies acknowledge that, in most cases, there is currently no viable pathway to achieve absolute zero for Scope 1 and 2 emissions, due to the hard-to-abate nature of most of their emissions. As a consequence, carbon offsets have been presented as a key strategy for neutralizing the remaining emissions and achieving long-term decarbonization goals. Strategies proposed include nature-based solutions (e.g., reforestation, afforestation, ecological restoration projects), carbon capture technologies (e.g., Direct Air Carbon Capture), and enhanced weathering methods (e.g., accelerated mineralisation of CO_2 through waste rocks removed from mineral deposits or the smelter slag from ferronickel operations). Most decarbonization roadmaps do not go into the details of the offsetting strategies that might be adopted and do not publicly disclose the expected volume of offsets required to achieve long-term decarbonization goals.

Fig. 2 summarizes the main features of current decarbonization roadmaps, highlighting the expected emissions reductions and the anticipated rollout of key technological solutions. Based on the corporate strategies assessed within the study, Fig. 2 offers a comprehensive qualitative overview of the pathways proposed within the industry to reduce operational emissions. The blue area represents a general reduction pathway, reflecting common targets within the industry, such as a 30% reduction by 2030 and 85-90% reductions by 2050 (although in most cases the magnitude of long-term reductions is not openly disclosed). The grey area indicates the expected contribution of carbon offsets used to neutralize the remaining emissions and achieve long-term targets. The hatched areas, instead, capture the variability and uncertainty surrounding the proposed pathways. For instance, the pace and scale of emissions reductions will vary depending on company-specific factors, and in some cases reductions might occur only after 2030 due to expected increases in production. Moreover, additional uncertainty arises from the limited transparency around the role of offsets and the reliance on breakthrough innovations (e.g., green hydrogen or process heat electrification) that are not yet widely deployable at commercial scales. This uncertainty translates in a wide range of potential outcomes in terms of emission reductions achievable by 2050.

Discussion

Considerations on existing decarbonization standards and targets

Although mining and metals companies have increasingly begun to define both short- and long-term emission reduction targets, there is currently no sector-specific methodology for target setting in this industry. Furthermore, most of the announced long-term Net Zero targets, to date, have not undergone formal validation under prevailing international standards. In the absence of a clear, unified sector-specific definition of Net Zero, and a harmonized framework for its implementation, assessing the consistency of these long-term decarbonization goals remains highly challenging.

This raises critical questions regarding the integrity of Net Zero targets in the mining and metals sector, including: i. What does Net Zero actually mean for the industry and how can this concept be translated into practice? ii. What constitutes a reasonable level of offset usage, and how can the sector ensure that the reliance on offsets does not undermine efforts to reduce emissions? iii. Should be Scope 3 emissions included into Net Zero targets, and if so, how should this be done?

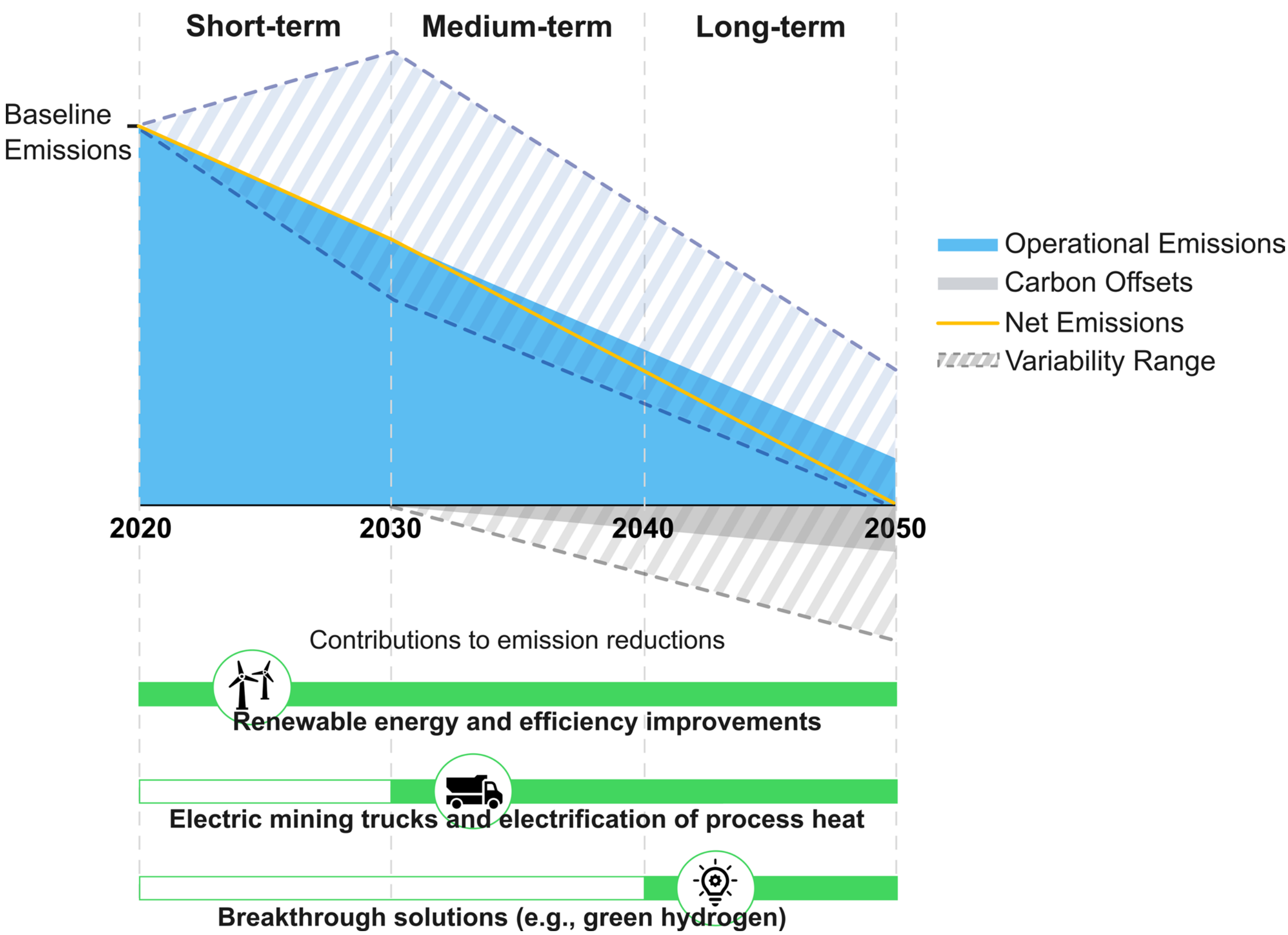

Fig. 2 Overview of the pathways proposed within the industry to reduce operational emissions, where Net emissions are considered equal to Operational emissions minus Carbon offsets

Firstly, as noted, no sector-specific target-setting methodology exists, and most long-term Net Zero targets lack validation under existing standards. This raises a critical issue, as the definition of the term Net Zero leaves room for interpretation (refer to Section"Interpretation of climate related key-terms") and requires the support of standards to establish a consistent and operational interpretation of the concept. In the absence of such validation, and given that companies rarely provide detailed disclosure of the adopted methodological approach, it remains unclear how the concept of Net Zero has been interpreted and applied across the sector.

Secondly, in most cases, the amount of carbon offsets required to achieve such targets is not transparently and openly disclosed. This lack of disclosure obscures the actual implications of Net Zero for the sector, particularly in terms of the absolute emissions reductions implied by these commitments.

Thirdly, it still remains uncovered whether Scope 3 should be included in the definition of Net Zero targets and it is uncertain whether existing approaches provide the most accurate accounting. Currently, most companies in the sector exclude Scope 3 emissions from their Net Zero claims, clearly neglecting a major source of emissions within the sector. In fact, for 17 out of the 20 companies considered in this study, upstream Scope 3 emissions represent on average 46% of their cradle-to-gate emissions (Scope 1 + 2 + 3 upstream) (see SM, Table S2). This raises concerns regarding the comprehensiveness of current decarbonization strategies and their alignment with global climate goals.

Despite this evident necessity, another critical consideration is whether a single Net Zero standard for the whole mining and metals industry is even feasible or meaningful, given the sector's inherent diversity. Mining and metals companies are generally diversified commodity producers, extracting and processing a range of different intermediate and refined metals, each with distinct carbon intensities and associated decarbonization challenges (Dietz et al. 2024) (see SM, Table S6). A single standard that fails to account for these differences might be overly simplistic and potentially unfair (Glencore 2024). On the other hand, adopting multiple Net Zero standards tailored to specific commodity supply chains poses its own challenges. Mining and metals companies, which cover different roles across various metals supply chains, might find it extremely difficult to comply with a wide variety of standards at the same time. This additional complexity, rather than shaping more effective emission reduction targets and strategies, could even slow-down progress towards decarbonization.

Resolving these issues will require extensive collaboration among industry representatives, standard developers, and policymakers.

How can the mining and metals industry achieve Net Zero in the long-term? Techno-economic challenges beyond 2030

Long-term Net Zero targets are widespread within the mining and metals industry, underscoring the ambition and the strong commitment of the whole sector towards decarbonization (IEA 2023). However, the feasibility of achieving these targets is highly uncertain (S&P Global 2024). As shown in Table 5, a significant portion of the strategies proposed to meet long-term goals relies on technologies that are not yet technologically or commercially mature (Wyns and Khandekar 2019), making their large-scale deployment currently speculative at best. This represents a major source of uncertainty. Moreover, most companies have not developed clear, detailed decarbonization roadmaps beyond 2030, limiting transparency around how these ambitious targets might be met – a second key source of uncertainty. Instead, long-term plans are currently reduced to vague statements of intent, lacking concrete steps and timelines. This makes it extremely difficult to assess whether and how Net Zero commitments will be achieved, raising serious concerns about the risk of greenwashing.

Moreover, companies frequently fail to address in their decarbonization roadmaps critical barriers for key long-term strategies, such as the transition to 100% renewable electricity, full fleet electrification, and the electrification of process heat. These solutions are often mentioned overlooking the substantial technological and economic challenges involved. In this context, we aim to highlight the barriers associated with some of these key strategies, emphasizing the importance of addressing these often-overlooked challenges to ensure that Net Zero targets are not merely symbolic, but realistically achievable.

Challenges for transitioning to 100% renewable electricity

The transition to renewable electricity is the central element of short-term decarbonization strategies. Today, many companies have already achieved or are planning to meet a high portion of their electricity demand through renewable energy by 2030, primarily via PPAs. However, achieving Net Zero in the long term will most likely require companies to cover their total electricity demand through renewables. This will be extremely challenging, particularly for off-grid remote operations, a common feature within the industry (Huang et al. 2024; IEA 2023). In such cases, while on-site renewable energy solutions often represent a simple strategy for reducing operational emissions, meeting the full electricity demand of these sites through renewable energy faces several obstacles. The main challenge is related to the inherent variability of renewable resources, which conflicts with the continuous and stable power supply demanded by mining and related processing activities (Igogo et al. 2021). Beyond technological challenges, fully meeting electricity demand through on-site renewable energy systems faces also notable economic barriers. Firstly, while becoming increasingly cost-competitive, renewable electricity solutions such as wind and solar have high initial capital costs, and might not be profitable for short mine lifespans (Issa et al. 2023). Furthermore, while battery energy storage systems are currently the most adopted storage solution for small-scale renewable projects, their high costs make them generally unfeasible for large-scale mining operations. Currently, the cost of electricity storage is the main limiting factor in achieving full decarbonization of off-grid sites, highlighting the need for significant technological advancements in this field in the coming years (Kalantari et al. 2021).

Moreover, the feasibility of renewable energy solutions is heavily dependent on site-specific factors, such as the local availability of renewable energy sources. While solar and wind technologies are by far the most preferred solutions due to their high technological maturity and economic competitiveness, they might not always represent a feasible solution for a full renewable electricity transition (Hazarabedian et al. 2024). In some cases, such conventional renewable energy solutions might be constrained by natural and climatic conditions, making the transition to 100% renewable electricity extremely challenging, if not highly improbable (Freeport-McMoRan 2023; National Grid 2023).

Challenges for full fleet electrification

Fleet electrification has been recognized by many leading mining and metals companies as the most promising strategy to eliminate the emissions from diesel-powered mining vehicles (Legge et al. 2021). Battery electric light vehicles are already being tested at multiple mining sites (Fortescue 2024; South32 2023; Vale 2024), and they are expected to be commercially available at scale in the near future. Many companies have set full fleet electrification as a key milestone on their path to Net Zero. However, achieving this goal can be particularly challenging. For instance, battery electric trucks may be less viable in cold-weather mines, as the efficiency of Lithium-ion batteries (LIBs) is reduced at low temperatures, leading to increased charging times, and subsequent lower production rates (Issa et al. 2023). Moreover, electrifying larger battery haul trucks, typical of open-pit operations, is still challenging due to low-energy density barriers (Clean energy finance corporation, minerals research Institute of Western Australia 2022). Today, the path towards full fleet electrification remains highly uncertain, and it's still unclear how companies intend to meet such target. Finding alternative solutions for decarbonizing in-mine material movement is therefore imperative and companies should explore a broader set of options to phase out diesel emissions at mine sites. In such situations, hydrogen-powered hauling trucks might be a more efficient and cost-effective solution, particularly for surface mines located in cold remote areas, as shown by Kalantari et al. (2021). However, these trucks currently face lower technological maturity and might reach commercial maturity much later than electric mining trucks, delaying potential emissions reductions (Legge et al. 2021).

Barriers towards the electrification of process heat

Strategies for the decarbonization of process heat will be essential for achieving long-term Net Zero targets within the industry. Direct electrification is frequently identified in existing roadmaps as a central strategy toward this goal. Today, multiple technologies for direct electrification of process heat are already available (Madeddu et al. 2020), but their applicability is strongly influenced by the range of temperatures required by each specific process, as well as the required energy densities, and temperature-time profiles. While many solutions for low to medium-temperature processes (up to 400°C) exist, technological barriers still limit in many cases the direct electrification of high-temperature processes (above 400°C) (Leicher et al. 2024). However, while significant, technological challenges are not the main reason for concern regarding the future widespread implementation of direct electrification solutions, which in many cases is expected to be limited by economic barriers. For instance, according to a recent study conducted by the Fraunhofer Institute for Systems and Innovation Research, technological barriers are likely to be overcome in virtually all applications within the sector by 2035. Nevertheless, at the same time, if not correctly addressed, economic and organisational challenges will strongly limit the extent to which direct electrification technologies could be implemented (Fraunhofer ISI 2024). Despite these concerns, existing long-term decarbonization roadmaps seem to overlook these significant barriers. As a result, it remains unclear how companies intend to address and overcome them on their pathways to Net Zero.

Challenges of increased electrification

Many of the most promising decarbonization solutions proposed within the industry rely on electrification, such as the adoption of electric mining fleets and the electrification of process heat. If successfully implemented, these measures will lead to a notable increase in electricity consumption. For instance, according to an analysis conducted by McKinsey & Company, electrification of a simple iron mine (through battery electric mining trucks and electric processing equipment) could already result in a doubling of its electricity demand (Henrio et al. 2023). Further electrification across subsequent processing and refining stages could drive electricity demand even higher for the production of a specific metal. The potential substantial increase of electricity demand due the implementation of electrification strategies represents a major challenge, yet largely underestimated. First, this rise in electricity consumption will likely necessitate the expansion and upgrading of existing grid infrastructure, generating notable economic and logistical challenges (BHP 2024; Müller-Falcke et al. 2023). Moreover, for off-grid operations, it will exacerbate the challenges of guaranteeing stable power demands through highly variable renewable energy sources. While these aspects will necessitate meticulous planning, they are still often overlooked in existing decarbonization roadmaps.

How to define targets and track progress towards Net Zero? The role of Life Cycle Assessment in decarbonization strategies

Within the industry, decarbonization targets are mainly defined at corporate level, with Scope 1 and 2 emissions typically separated from Scope 3, and the latter often excluded from long-term commitments. While common practice, this approach risks creating a misleading picture of decarbonization progress and may limit the effectiveness of corporate strategies in delivering genuine Net Zero outcomes.

A first major issue concerns the way low-carbon technologies are accounted for. Corporate decarbonization roadmaps generally classify measures such as renewable energy, battery electric mining trucks, and other clean-tech solutions as zero-GHG strategies, on the basis that they eliminate direct operational emissions (Scope 1 and 2). Yet, these solutions are associated with relevant volumes of indirect emissions linked to raw material extraction, components manufacturing, and the construction of supporting infrastructure. As a result, labelling these solutions as zero-GHG hides the indirect emissions that contribute to their real carbon footprint.

On a full life cycle perspective, renewable energy solutions are still associated with a non-negligible amount of emissions, which are generated during the manufacturing of the technologies themselves, as well as the supporting infrastructure and the storage systems required for their deployment (Amponsah et al. 2014; Arvesen et al. 2011; Yang et al. 2023). Similarly, Balboa-Espinoza et al. (2023) showed that although battery electric mining trucks can substantially reduce overall emissions compared to conventional mining trucks, their production results in 33% higher GHG emissions – primarily due to the raw materials needed for battery manufacturing. Neglecting these indirect upstream emissions can underestimate the true carbon footprint, as such solutions can shift a portion of current Scope 1 and 2 emissions into Scope 3. Therefore, adopting a more holistic perspective that includes indirect emissions is essential to ensure the credibility and effectiveness of long-term decarbonization strategies.

A second major issue is that Scope 3 emissions are far from negligible in several metals supply chains (see Table 6). For instance, chemical reagents have been often identified as one of the main hotspots in the production of lithium, cobalt, and nickel (Bartzas and Komnitsas 2024; Cobalt Institute 2022; Schenker et al. 2022).

It should therefore be clear that without effective strategies to reduce Scope 3 emissions, a true Net Zero target might be out of reach.

In this context, the application of the Life Cycle Assessment (LCA) methodology for setting decarbonization targets and monitoring progress towards Net Zero certainly present significant benefits. Such benefits include: i. a comprehensive estimate of all emissions associated with the metal commodity supply chain, encompassing Scope 1, 2 and 3; ii. the inclusion of upstream (indirect) emissions associated with decarbonization strategies technologies themselves; iii. the possibility of an early quantification of emission reductions achievable through specific decarbonization strategies, thus enabling the identification of the most effective scenarios to reach Net Zero; iv. the assessment of other potential environmental impacts beyond GHGs emissions, which is crucial to avoid potential environmental trade-offs.

Despite being universally accepted as a scientifically robust methodology, LCA is not yet widely adopted to define decarbonization strategies. However, LCA is gaining traction within the mining and metals industry, driven in part by the growing need to comply with emerging regulations (Santero and Hendry 2016). Today, many companies in the sector are already using LCA to transparently report the environmental impacts associated with their products (Albemarle Corporation 2024; Boliden AB 2024; SQM 2021; Terrafame Ltd 2022), and several industry associations have developed specific guidelines to standardize carbon footprint calculations and support the sector's efforts towards transparency and decarbonization (International Copper Association 2022; Cobalt Institute 2023; International Lithium Association 2024; International Zinc Association 2024). These promising advancements offer an opportunity for developing new Net Zero standards based on product carbon footprints, potentially driving emissions reduction efforts within all aspects of the mining and the metals industry. The copper industry is leading the way towards this goal, and is currently developing a copper specific 1.5°C-aligned target setting methodology to enable copper producers to establish intensity-based targets inclusive of Scope 1, 2 and 3 emissions (The Copper Mark, RMI 2024).

Conclusions

Over the past few years, and thanks to the contribution of multiple industry-wide initiatives, decarbonization has become a high-priority topic of discussion within the mining and metals industries. Nearly all the leading companies within the sector have in fact set ambitious decarbonization targets, with many aiming to achieve *Net Zero operational emissions* (Scope 1 and 2) by 2050.

An analysis of the decarbonization roadmaps proposed by twenty major mining and metals companies suggested the following average trajectory: (1) a massive deployment of renewable energy is expected to drive substantial emissions reductions in the short-term (before 2030); (2) between 2030 and 2040, further reductions will be achieved through the widespread implementation of electric battery mining trucks and the direct electrification of process heat; (3) ss a last step, Net Zero operational emissions by 2050 will be achieved by a mix of breakthrough technologies and carbon offsets. Despite such ambitious goals, sometimes underpinned by clear roadmaps and remarkable investment agendas, at least for the next decade, which is already a remarkable achievement, some questions remains open. This paper has contributed to frame the questions and suggest elements of a possible response or way forward.

> *(Open question 1)*. Decarbonization strategies are often limited to Scope 1 and 2 and companies sometimes untransparently rely on *carbon offsets* to neutralize hard-to-abate emissions. Unfortunately, most decarbonization roadmaps are rather vague when specifying how large such offsets are and in which way they will be implemented. This uncertainty, combined with the lack of industry-specific standards, creates more than some

Table 6 Contribution of Scope 3 emissions to the Carbon Footprint (CF) of selected metal compounds.

Metal compound	Production route	CF [$kg_{CO_{2,eq}} kg^{-1}_{product}$]	Contribution of Scope 3 emissions to CF [%]	Sources
$NiSO_4 \cdot 6H_2O$	Indonesian nickel laterite *via* High Pressure Acid Leaching	8.2	32	Bartzas and Komnitsas (2024)
	Canadian nickel sulfide *via* pyrometallurgy	1.6	41	Tijsseling and Whattoff (2023)
	Indonesian nickel laterite *via* High Pressure Acid Leaching	7.3	29	
$LiOH\ H_2O$	Lithium brine extracted at Salar de Atacama	7.7	36[1]	Istrate et al. (2024)
	Australian spodumene refined in China	17.2	16[1]	
Li_2CO_3	Lithium brine extracted at Salar de Atacama	3.4	38[1]	Schenker et al. (2022)
	Lithium brine extracted at Salar de Olaroz	7.4	75[1]	
	Lithium brine extracted at Salar de Cauchari-Olaroz	7.7	65[1]	
	Lithium brine extracted at Salar del Hombre Muerto	7.9	75[1]	
$CoSO_4 \cdot 7H_2O$	Average of global operations excluding China	4.0	70	Cobalt Institute (2022)
	Copper-Cobalt ores from the DRC[2] *via* hydrometallurgy and refined in China	15.0	62[1]	Istrate et al. (2024)

[1] Values refer to the contribution of chemical reagents only; in these cases the contribution of Scope 3 emissions might be even higher.

[2] DRC: Democratic Republic of Congo

confusion around the interpretation of the concept of Net Zero. Addressing this issue will require industry-specific standards for the inclusion or exclusion of Scope 3 emissions and a quantitative ceiling (e.g., 10-15%) for the *use of carbon offsets*, both key elements to ensure a transparent and operationalized definition of Net Zero.
(Open question 2). Because long-term strategies depend on solutions that are not yet technologically or commercially mature, Net Zero ambitions in the long-term are at risk, as well as the risk of greenwashing is high. A tool or framework is needed for an early-stage assessment, or ranking, of the mitigation potential in case of multiple options, in order to identify the most promising solutions, or overcome the challenges. A special attention should be given to the techno-economic barriers highlighted in this study, which are often overlooked. Today, given the currently limited level of technological development and economic feasibility of many of the decarbonization solutions proposed, most of the leading companies within sector have not yet developed detailed decarbonization roadmaps beyond 2030.
(Open question 3). Decarbonization roadmaps often lack targets and related strategies for reducing Scope 3 emissions, clearly neglecting a major source of emissions in the sector. In fact, for 17 out of the 20 companies considered in this study, upstream Scope 3 emissions represent on average 46% of their cradle-to-gate emissions (Scope 1 + 2 + 3 upstream). Here, we argue that the LCA methodology certainly represents a more effective and scientifically robust method to define targets and track progress towards Net Zero. Among its several benefits, we believe that its adoption could help the sector to measure and mitigate more effectively its Scope 3 emission.

All these aspects highlight the urgent need for clearer frameworks to guide the industry on a credible and transparent path towards Net Zero.

Supplementary information

The Article has accompanying supplementary file/s (Supplementary information Material - SM).

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Data Availability All the sources of data have been quoted throughout the text. A supplementary file has been provided containing all the relevant references used concerning reports/information about mining Companies and other collected data.

Declarations

Conflict of 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. The authors only declare that the research work has been developed within the activities of the Horizon Europe project METALLICO (GA 101091682) and therefore, supported by the project itself.

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