



Essential Minerals Coalition

Role of the Mining Sector in
decarbonization and energy transition

Full study

Technical Information

Technical Information Sheet Essential Minerals Coalition: Role of the mining sector in decarbonization and energy transition

© 2025 Brazilian Business Council for Sustainable Development (CEBDS). All rights reserved.

Study conceived and coordinated by the Brazilian Business Council for Sustainable Development (CEBDS), Vale, and

the Brazilian Mining Association (IBRAM), with technical support from the Boston Consulting Group (BCG).

CEBDS:

Marina Grossi | President

Alessandra Fajardo | Executive Technical Director

Daniela Mignani | Executive Corporate Director

Technical Team:

Viviane Romeiro | Technical Director for Climate and Energy

Lucas Grilo | Senior Technical Manager for Sustainable Finance and Circular Economy

Lucas Costamilan | Technical Manager for Climate and Energy

João Leal | Climate Policy Manager

Bruna Valença | Technical Analyst for Climate and Energy

Melissa Pesconi | Technical Analyst for Sustainable Finance and Circular Economy

Isadora Sartini | Climate and Energy Intern

Communications Team:

Philippe Deschamps | Communications Manager

Joice Coletti | Communications and Press Relations Coordinator

Renata Pinheiro | Communications, Marketing, and Events Coordinator

Arianny Dias | Communications, Marketing, and Events Analyst

Josilene Rocha | Communications and Press Relations Analyst

Lucas Guimarães | Communications, Marketing, and Events Analyst

Institutional Relations Team:

Sueli Mendes | Institutional Relations Manager

Pedro Augusto | Institutional Relations and Fundraising Coordinator

Raquel Pereira | Institutional Relations Analyst

João Santiago | Data and Institutional Relations Intern

Coalition Member Companies:

VALE | IBRAM | ABAL | AMBIPAR | ALCOA |
ANGLOAMERICAN | CBA | CBL | MICHELIN |
GRUPO REPORT | SAMARCO | SIEMENS | SIGMA
LITHIUM | TABOCA

Other intellectual property rights belong to CEBDS, BCG, Vale, IBRAM, and supporting companies.

YEAR

2025

CEBDS Social Media:

cebds.org

Facebook.com/CEBDSBR

x.com/CEBDS

Youtube.com/CEBDSBR

Instagram.com/cebdsbr

linkedin.com/cebds

CEBDS Address:

BQ Escritórios – Rua São José, 40, 3rd floor – Centro – Rio de Janeiro, RJ

ZIP Code: 20010-020

Phone: +55 (21) 2483-2250

E-mail: cebds@cebds.org

Suggested citation:

CEBDS – Brazilian Business Council for Sustainable Development.

Essential Minerals Coalition: Role of the mining sector in decarbonization and energy transition. Rio de Janeiro, October 2025.

About this report

This report is the result of the joint effort of a wide group of organizations linked to the Brazilian mineral sector, all coordinated by CEBDS, Vale, and IBRAM. The purpose of this study is to create a consolidated overview on how Brazilian mining contributes to global decarbonization and the transition to clean energy.

This perspective includes an analysis of the feasibility of decarbonizing mining in Brazil by 2050, possible contributions to the iron ore chain, and the potential for the extraction and processing of minerals to be used in various applications to support the transition to cleaner energy sources. The study also describes certain mechanisms that will require coordinated actions from multiple parties and are essential for implementing the contributions that were analyzed in the study.

The scenarios and predictions presented are based on assumptions and recognized sources, which include publications from the Brazilian Mining Institute (IBRAM) and the International Energy Agency (IEA), Study Papers of the National Mining Plan 2050 and sectoral Coalitions on Transportation and Energy, which are also coordinated by the Brazilian Business Council for Sustainable Development (CEBDS), among other sources.

Introduction

By Marina Grossi

*President of CEBDS and Special Envoy
for the Business Sector to COP30*

Critical minerals are one of today's main pillars of the global energy transition. Elements such as lithium, nickel, copper, niobium, and rare earths underpin the production of batteries, electric vehicles, wind turbines, and digital technologies that are essential for decarbonization.

In this context, Brazil holds a strategic position. The country combines vast diversity and volume of mineral reserves, a predominantly renewable energy matrix, and well-established technical institutions. This combination grants the Brazilian mining sector the ability to produce critical inputs with lower carbon intensity, transparency, and traceability — attributes increasingly demanded by global value chains.

With this purpose, and at the invitation of Ambassador André Corrêa do Lago, President of COP30, CEBDS coordinated the **Business Coalition on Critical Minerals**, in partnership with **Vale** and **IBRAM**.

The initiative brought together **25 companies and associations** in a collaborative effort that outlines a **national strategy for a transition to low-carbon mining**, with concrete goals and instruments.

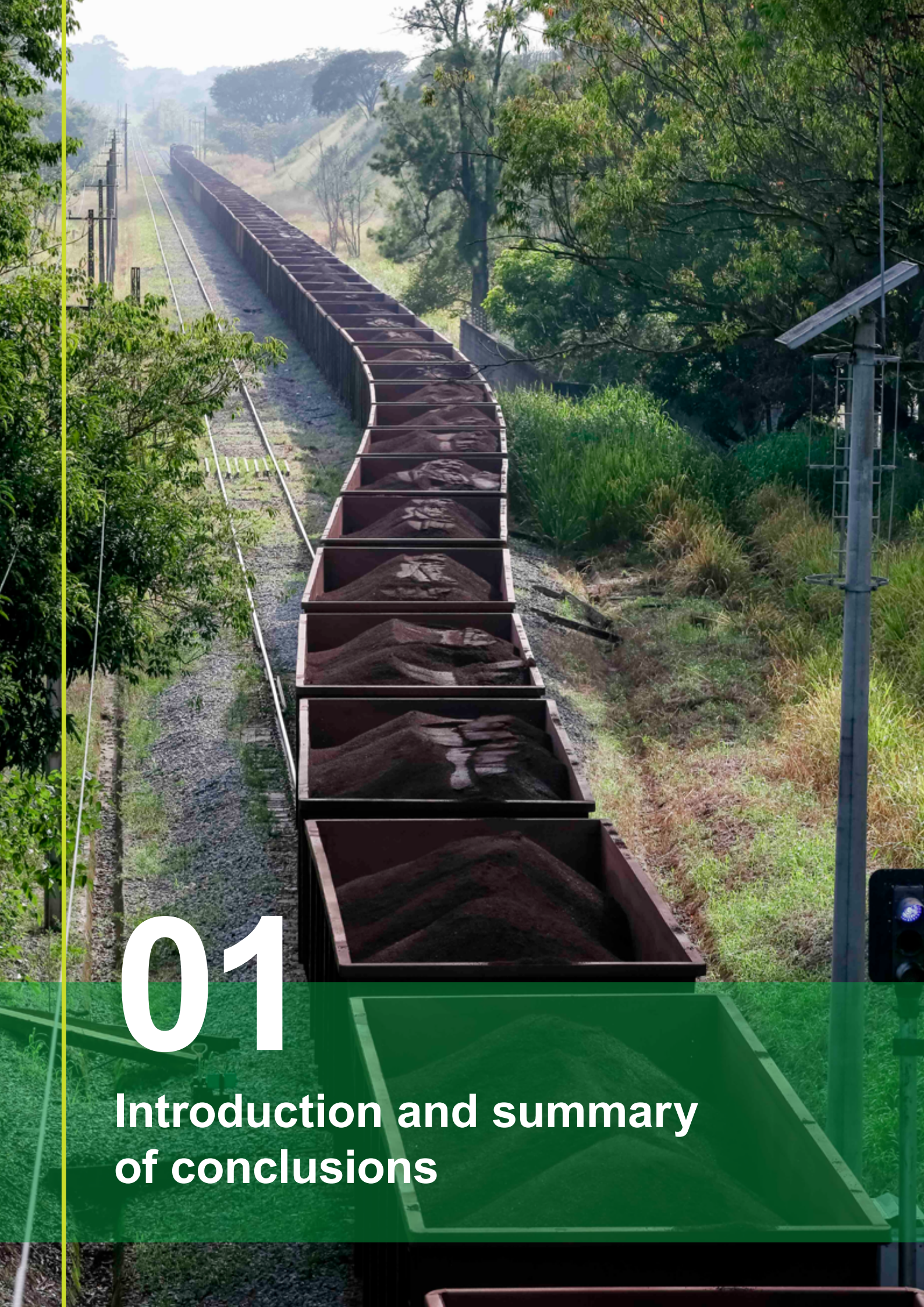
The study shows that the sector can **reduce up to one-third of its direct emissions by 2035** by expanding the use of clean energy, electrifying processes, and adopting operational efficiency technologies. It also highlights pathways to consolidate Brazil as a **reliable supplier of critical minerals**, adding value to production while ensuring alignment with international standards of sustainability and environmental governance.

More than a diagnosis, this Coalition represents a **business commitment to the future of the mining sector**. It embodies the convergence of competitiveness, legitimacy, and innovation, recognizing that Brazil's mineral leadership will depend on the coherence between productivity, climate action, and social governance.

It is about turning a **natural advantage into effective climate leadership**, contributing to a global transition based on value, transparency, and cooperation.

Contents

1 Introduction and summary of conclusions	6	5 Enablers for the decarbonization of the mineral sector and expansion of minerals for the energy transition	40
1.1 The global energy transition and Brazil's position	7	5.1 Technology and R&D	41
1.2 The Essential Minerals Coalition: origin and purpose	7	5.1.1 Hydrogen and cost reduction	42
1.3 Summary of findings: mining contribution opportunities and enablers needed	9	5.2 Infrastructure	43
2 Emissions from the mining sector and decarbonization opportunities	10	5.2.1 Production, distribution and storage of biofuels	43
2.1 Defining a future emission scenario of inaction, or business-as-usual	12	5.2.2 Expansion of the electric power transmission and distribution grid to support electrification	43
2.2 Mapping levers to reduce and predict the impact of contributions	14	5.2.3 Infrastructure for mineral production logistics	43
2.2.1 Replacement of fuels	17	5.3 Funding	45
2.2.2 Electrification and power-to-X	18	5.4 Green Premium and Value Chain	46
2.2.3 Renewable energy	19	5.4.1 Accounting and traceability mechanisms	46
2.2.4 Efficiency and innovation in processes	19	5.4.2 Circularity	46
2.2.5 Land use and forests	19	5.5 Regulatory-Economic Scenario	48
3 The iron ore supply chain: the mining sector and its role in decarbonization	21	5.5.1 Predictability and agility of licensing	48
3.1 Expansion of inputs for low-carbon steel production	23	5.5.2 Carbon pricing and the Brazilian Emissions Trading System	49
3.2 Collaboration with suppliers in long-haul shipping	26	5.5.3 Accounting for solutions related to both land restoration and carbon sequestration	50
3.3 Decarbonization of the pelletizing stage	26	5.6 International Enablers and COP30	50
3.4 Reduction of logistical emissions linked to rail transport	30	6 Appendix	52
4 Minerals for the energy transition: expanding production and contributing to global decarbonization	31	6.1 Sources	53
4.1 Expansion of mineral production for the energy transition	32	6.2 Long list of levers evaluated	54
4.1.1 Selection of ores for quantification	32	6.3 Assumptions for modeling	55
4.1.2 Growth projections of Brazilian production	36	6.4 Details of mineral production projections for the energy transition	58
4.2 Emissions impact	37	6.4.1 Bauxite	58
4.2.1 Global emissions impact in 2050	37	6.4.2 Manganese	58
4.2.2 Impact on Brazilian emissions in 2035 and 2050	38	6.4.3 Copper	59
		6.4.4 Zinc	59
		6.4.5 Silicon	60
		6.4.6 Niobium	60
		6.4.7 Nickel	61
		6.4.8 Graphite	61
		6.4.9 Vanadium	62
		6.4.10 Metallic Lithium	62
		6.4.11 Lithium	63
		6.4.12 Tantalum	63
		6.4.13 Rare Earths	64
		6.4.14 Cobalt	64



01

**Introduction and summary
of conclusions**

1.1 The global energy transition and Brazil's position

Mining will play a critical role in the global energy transition, driven by the accelerating demand for transition-enabling technologies and the continued importance of traditional mineral resources. This process creates strategic opportunities, but also poses the danger of becoming overly reliant on other regions or countries responsible for current and future supply.

From a global point of view, there are three key trends:

- **An increase in the volume and development of new areas of exploration and supply chains of minerals for the energy transition** (lithium, nickel, graphite, etc.), essential for batteries, electric mobility and renewable generation;
- **A growing significance of the demand for well-established minerals in the context of the energy transition** (such as iron and bauxite), driven both by direct applications in the energy transition and by the expansion of associated infrastructure (e.g., electrical grids);
- **Higher risks associated with productive concentration and geopolitical tensions**, which increase the vulnerability of global supply;
- **An evolution and reconfiguration of the mineral beneficiation and processing chains, globally**, motivated by economic factors, sustainability requirements, and predictability of input supply.

Against this backdrop, Brazilian mining is well positioned as a strategic enabler of the energy transition, leveraging its unique competitive strengths:

- **Its geological diversity is among the most expansive in the world**, encompassing multiple minerals that will see their demand multiplied in the coming decades;
- **A well-developed mineral sector, renewable electricity matrix and competitive energy and labor costs**, which favor projects that have lower carbon intensity and enhanced international competitiveness;
- **Recognized as a supplier that is sustainable and possesses good governance**, based on having strong institutional structures and continually improving regulations;

- **Potential alignment between climate goals and local value creation**, allowing mineral production to be associated with sustainable development and green industrialization policies.

In order for these opportunities to become tangible, it **will be crucial to make progress in systemic enablers** such as technology and research, infrastructure, financing, regulation, and value chain alignment mechanisms, creating the necessary conditions for the mineral sector and downstream value chains to contribute effectively and sustainably to the energy transition.

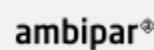
1.2 The Essential Minerals Coalition: origin and purpose

The Essential Minerals Coalition was a result of the activities initiated by the "Global Task Force" under the COP30 Presidency. Uniting companies, associations, specialists, and government officials, the Coalition successfully forged a shared vision that links the Brazilian mineral sector's contributions to domestic and global decarbonization and energy transition commitments. This collaborative effort leveraged sectoral reports and included workshops and interviews to incorporate the knowledge and visions of the Coalition, ultimately resulting in this report that summarizes the potential positive impact of the sector and the systemic enablers necessary to achieve that potential.

Coordinating group



Participating organizations



The Coalition's effort was based on a solid foundation of existing knowledge from both Brazil and internationally. Among the multiple sources used, noteworthy publications included the Brazilian Mining Institute (IBRAM), the International Energy Agency (IEA) and the Study Papers of the National Mining Plan 2050. The full list of sources can be found in the Appendix.

Mining permeates various economic, social and environmental dimensions, influencing spatial planning, food production, industrial goods, energy and the preservation of biodiversity. The Coalition's work prioritized the relationship between Brazilian mining and global decarbonization and energy transition, defining possible contributions from the sector in three analysis approaches: **(1) reduction of direct emissions from Brazilian mining; (2) contributions from Brazilian mining to the global iron ore and steel chain; and (3) expansion of mineral production to sectors related to the energy transition.** These three scopes of analysis are quite different from each other, as described below.

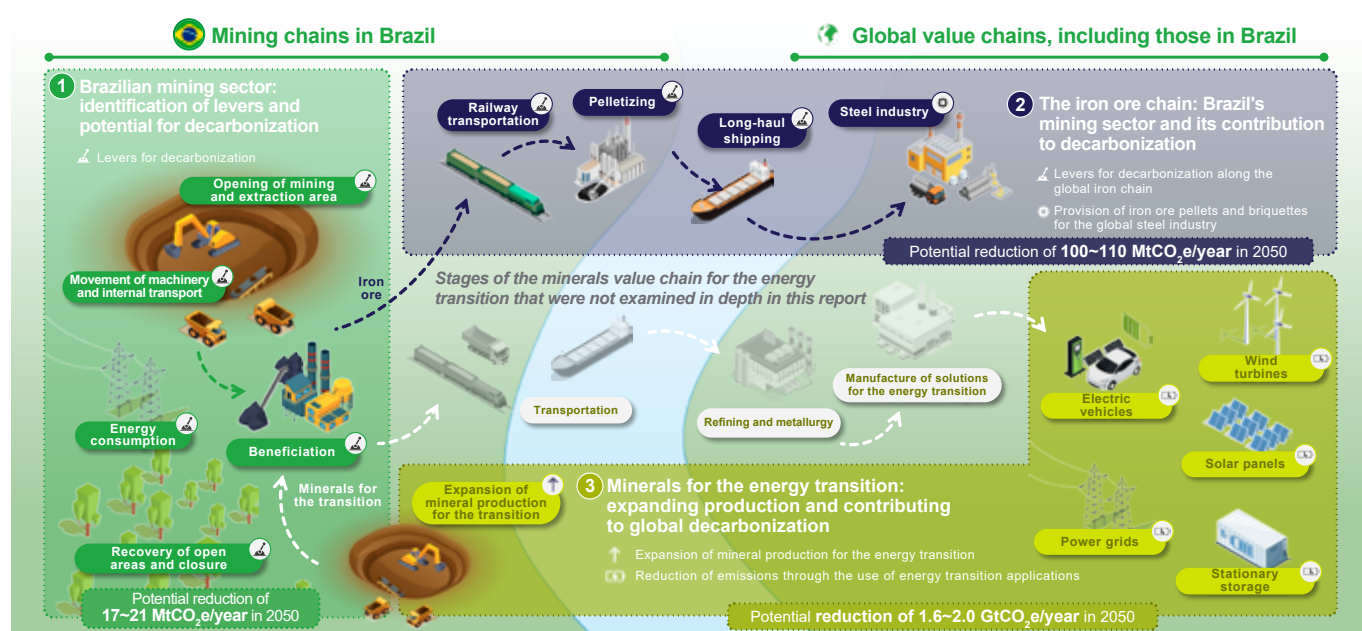
Direct emissions from mining reached 12.8 MtCO₂e in 2022 according to IBRAM's Greenhouse Gas Emissions Inventory, which considers emissions nationwide associated with the stripping and opening of a mining front, extraction, physical processing, movement of machinery and internal transport, recovery and closure of areas. The inventory therefore does not include emissions associated with rail transport or long-

distance shipping, nor linked to beneficiation activities that go beyond the physical treatment of ores—for example, the pelletizing of iron ore. This amount is relatively minor when viewed in relation to the emissions produced by Brazil as a whole or by the value chains driven by mining activities.

Observing the **Brazilian iron ore chain**, the Coalition estimated current emissions between **85 and 90 MtCO₂e** covering the stages of pelletizing (2.5-3.5 MtCO₂e), rail transport (~2 MtCO₂e), maritime transport (15-20 MtCO₂e) and the national steel industry (65 MtCO₂e¹). On a global scale, the steel industry, fed by exports of Brazilian iron ore, was responsible for 3.6 GtCO₂e.

Finally, the minerals extracted in the country are **essential inputs for energy transition technologies**, which will play a tremendous role in reducing global emissions in their stage of use by replacing technologies with fossil emissions. In this study, electric vehicles (EVs), solar panels and wind turbines are viewed as solutions capable of reducing emissions. According to Climate Trace data, these solutions impact a large portion of current global emissions, totaling **~23 GtCO₂e** (~15.8 GtCO₂e from the power sector, excluding CCUS mitigation potential for fossil fuels; ~3.9 GtCO₂e from residential emissions, excluding residual emissions; and ~3.6 GtCO₂e from road transport, excluding residual emissions and biofuels mitigation potential).

Figure 1 – Scopes of contribution of Brazilian mining to decarbonization and the global energy transition



1. According to the World Steel Association

1.3 Summary of findings: mining contribution opportunities and enablers needed

The **reduction of direct emissions from mining**, 12.8 MtCO₂e in 2022, will depend on levers like the use of biofuels, fleet electrification, expansion of the use of renewable energy, efficiency gains, and recovery of areas to neutralize residual emissions.

- Assuming the deployment of technologies with anticipated technical and economic feasibility **by 2035**, and factoring in carbon pricing as outlined in the Enablers chapter, **emissions could be reduced by 25%-35%. This includes an additional ~14% offset from land-use measures**, leading to **residual emissions of 50%~60%** relative to a baseline of 15-17 MtCO₂e under a scenario of inaction;
- By **2050**, considering the acceleration of the global energy transition and the development of systemic enablers, the sector identifies additional emission reduction potential, reaching net **residual emissions of ~10%** compared to the inaction scenario of 18-24 MtCO₂e.

The aforementioned net residual emissions rely on accounting for carbon removals to neutralize land-use emissions in corporate inventories. This accounting is not allowed in the current GHG Protocol methodology, but it is an opportunity to facilitate mining companies' carbon neutrality goals, as discussed in the *Enablers* chapter.

Mining can also **help reduce emissions along the global iron ore chain** with the production of inputs (pellets and briquettes) for low-carbon steel, reduction of emissions in pelletizing, railways and long-distance shipping:

- Contributions can enable **reductions of 100-110 MtCO₂e in 2050** in the global iron ore chain.

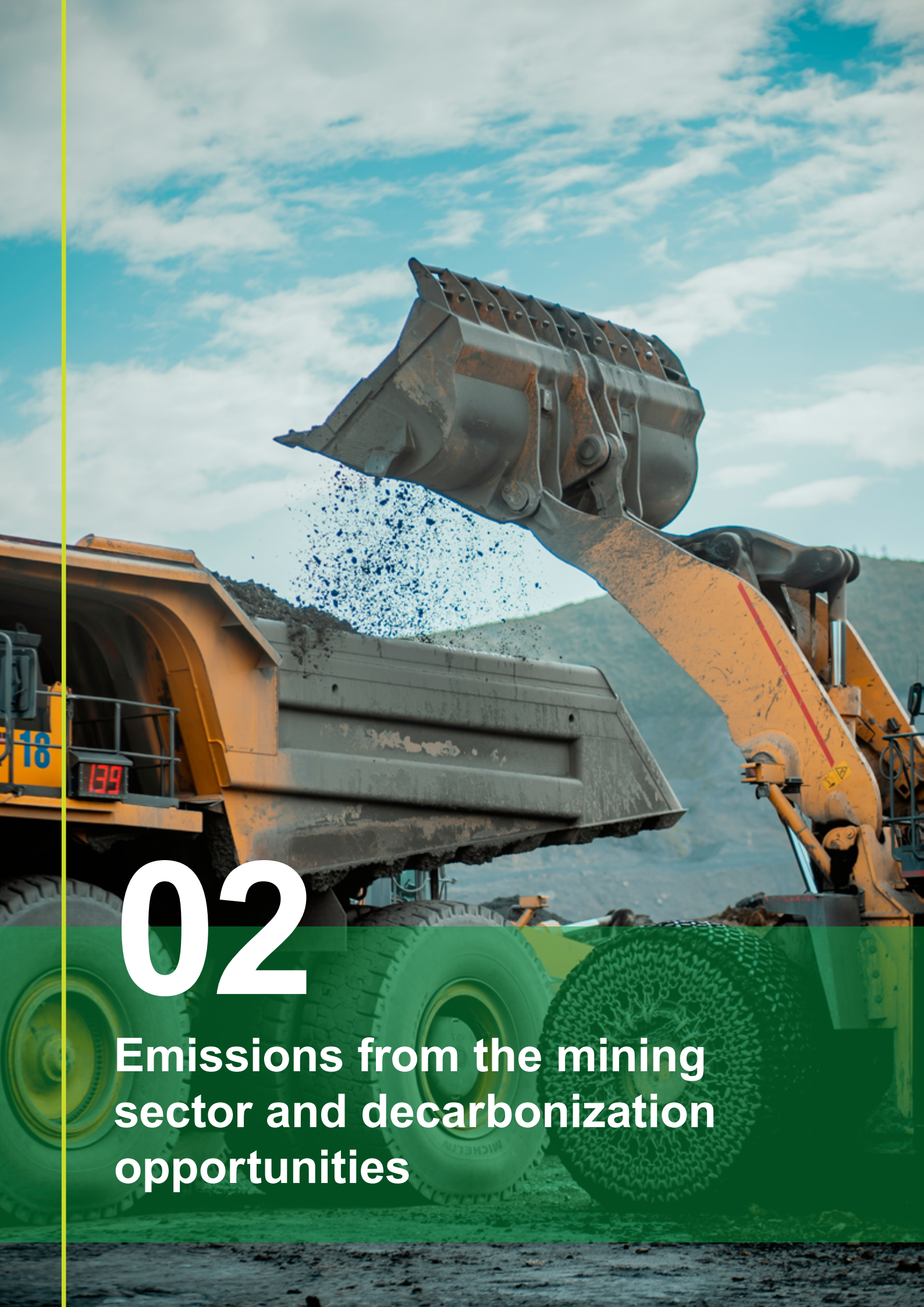
Finally, **expanding mineral production to enable solutions for the global energy transition**—such as vehicle electrification, expansion of solar and wind generation, electrical grids and storage systems—can help prevent:

- **1.6-2.0 GtCO₂e of global emissions in 2050;**
- Of which **260-300 MtCO₂e can be prevented in Brazil.**

Realizing **these contributions requires the development of systemic enablers that transcend the mining sector's** direct control. These prerequisites must be collaboratively refined with the value chain, financiers, the government, and other parties:

- Regulatory-economic scenario: alignment of **economic incentives and carbon pricing** that guide investments in low-carbon technologies, in addition to **regulatory improvements to enable the sustainable expansion of production**—including agile and predictable licensing—and the necessary supply chains and infrastructure, ensuring the competitiveness of domestic products;
- Technology and R&D: development of **critical technologies that are not only technically mature, but also economically viable**, while accounting for carbon pricing, in addition to developing skills for local beneficiation of minerals and greater value capture;
- Infrastructure: **logistics, energy and storage network with sufficient distribution** and capacity to serve both ongoing operations and new projects;
- Financing: **green financial instruments and sustainable taxonomy** capable of reducing risks and boosting access to capital at scale for low-carbon initiatives;
- Green premium and value chain: an integrated ecosystem featuring **predictable demand** for low-carbon mineral products and **tracking mechanisms** that align incentives along the entire value chain.

Note: Reducing and neutralizing 90% of mining emissions in 2050, 17-21 MtCO₂e, would be equivalent to the annual emissions of 8-10 million gas-oline-powered vehicles. A reduction of 100-110 MtCO₂e in the iron ore chain would be equivalent to another 50~55 million vehicles, which is close to the Brazilian fleet of EVs projected for 2050. A global reduction of 1.6-2.0 GtCO₂ from energy transition solutions is comparable to total Brazilian emissions, which were ~2.3 GtCO₂e in 2023.

A large yellow excavator bucket is shown in the process of dumping a load of dark, granular material into the bed of a yellow dump truck. The excavator's arm and bucket are positioned above the truck's bed, with a spray of dust or small particles visible as the material falls. The dump truck is a large, heavy-duty vehicle with a prominent front grille and large tires. The background shows a hilly, open-pit mine landscape under a blue sky with scattered white clouds. The overall scene is industrial and captures a key moment in the mining process.

02

Emissions from the mining sector and decarbonization opportunities

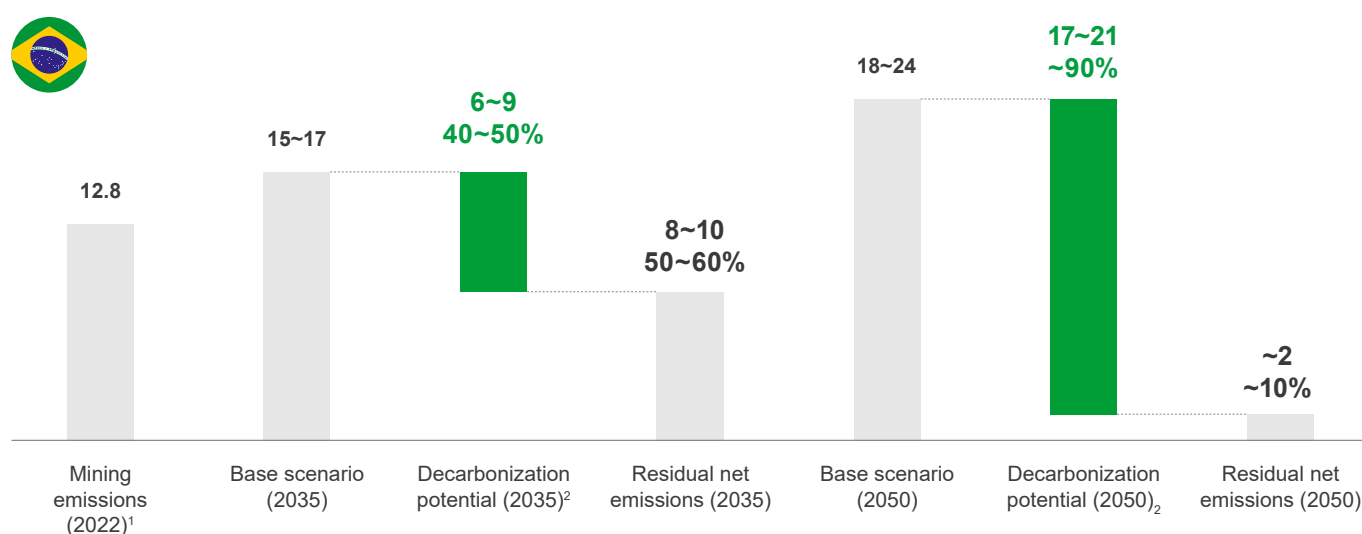
Considering current emissions of approximately **12.8 MtCO₂e** (2022), the projected volume increase for domestic production, if not combined with measures to reduce emissions intensity, would lead the sector to reach between **15 and 17 MtCO₂e in 2035 and up to 24 MtCO₂e in 2050**.

As systemic conditions improve and the energy transition gains momentum, the evaluated decarbonization levers demonstrate strong potential to drive substantial emission reductions. Studies conducted by the Coalition suggest that emissions could be reduced and neutralized by up to **40%-50% in 2035**. Over a longer-term view, with greater uncertainty

associated with systemic enablers (discussed in detail in the Enablers chapter), the sector believes that it is potentially possible to reduce and neutralize **up to 90% of emissions in 2050**.

Even after all levers are implemented, there will be **residual emissions of around 10% in 2050**, which could be neutralized by nature-based solutions and additional offsetting mechanisms. International corporate inventory standards have yet to address the use of neutralization and offset mechanisms by mining companies to meet their emission reduction targets—a topic discussed further in the Enablers chapter.

Figure 2 – Mining and energy consumption (Net emissions¹, MtCO₂e)



1. Considers emissions from mining activities in the IBRAM Emissions Inventory relating to the stages of stripping and opening of the mining front, extraction, beneficiation, movement of machinery and internal transport, recovery of open areas, closure of these areas, and acquisition of electricity. Considers net land-use emissions, assuming carbon removal by recovered areas equivalent to annual emissions 2. Assumptions consider the availability of alternative fuels to diesel, technologies for decarbonizing the fleet and the validity of a carbon price that makes the cost of reducing the sector's emissions viable, between \$65-\$100/ton in 2035 and \$160-\$200/ton in 2050.

Sources: IBRAM; National Mining Agency; Wood Mackenzie; Studies for the National Mining Plan (PNM) 2050; International Energy Agency (IEA); Coalition discussions

Within this framework, five groups of levers are particularly prominent as determinants:

- (i) **replacement of fossil fuels** in fleets and equipment;
- (ii) **electrification and power-to-X¹** as energy vectors;
- (iii) **efficiency gains and technological innovation** in mines and industrial plants;

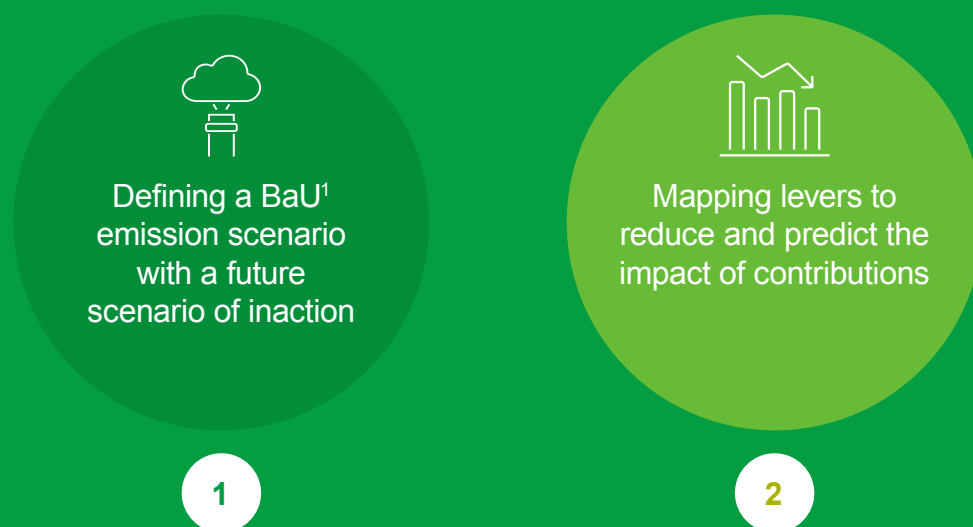
- (iv) **expansion of renewable energy** via local generation and long-term contracts;

- (v) **sustainable land use and reforestation** to neutralize residual emissions.

A coordinated implementation of these solutions can substantially reduce the sector's emissions, while creating investment opportunities and strengthening Brazil's position as a reference in low-carbon mining.

1. Power-to-X (PtX) is the term used to describe technologies that convert electricity, usually from renewable sources like solar and wind, into different energy and fuel vectors, such as hydrogen.

Two steps will be involved in defining the pathways to decarbonization



1. Business-as-usual, no decarbonization actions

2.1 Defining a future emission scenario of inaction, or business-as-usual

Gross emissions from the Brazilian mineral sector totaled approximately **12.8 MtCO₂e** (scopes 1 and 2) in 2022, according to the emissions inventory of the sector developed by IBRAM, considering 27 mineral typologies. **Mobile combustion** accounts for nearly 60% of emissions, primarily associated with the use of diesel in off-highway trucks and heavy equipment. Another 14% are linked to **changes in land use**, resulting from the opening of new mining fronts and vegetation suppression. **Stationary combustion**, linked to boilers, furnaces and generators, represents 9% of the total. In addition to these sources, the **consumption of electricity** (scope 2) accounts for another 12%.

These four categories (mobile combustion, land use, stationary combustion, and purchased energy) account for approximately **95% of all sector emissions**, establishing them as the priority areas for climate action. Other sources, such as fugitive emissions, industrial processes and waste, have a less representative share of the sector's total inventory.

It is important to point out that, when it comes to **land use**, the recovery of areas by mining companies—either as a regulatory obligation or a voluntary initiative—can result in net emissions that are close to zero or even negative, depending on the time frame considered.



Figure 3 – Gross emissions from the mining sector¹ (MtCO₂e – % of scopes 1 and 2, 2022)



1. The figures presented are an estimate for the mineral sector based on data reported by participating companies and assumptions. Due to the differences in the operational, technological and geographical characteristics of the companies, these amounts do not necessarily represent the individual emissions of each organization 2. Accounting for net land use emissions depends on international methodological developments. This study assumes the potential for future harmonization of measurement standards and the feasibility of emissions offsetting (e.g., GHG Protocol methodology)

Source: IBRAM, Inventory of greenhouse gas emissions from the mineral sector 2024 – Base Year 2022

At current carbon intensities, Brazilian mining emissions could grow between **45% and 85% by 2050**, driven by rising mineral production. The scenario of inaction illustrates that emissions, which today represent **12.8 MtCO₂e**, could reach up to **23.6 MtCO₂e** in 2050.

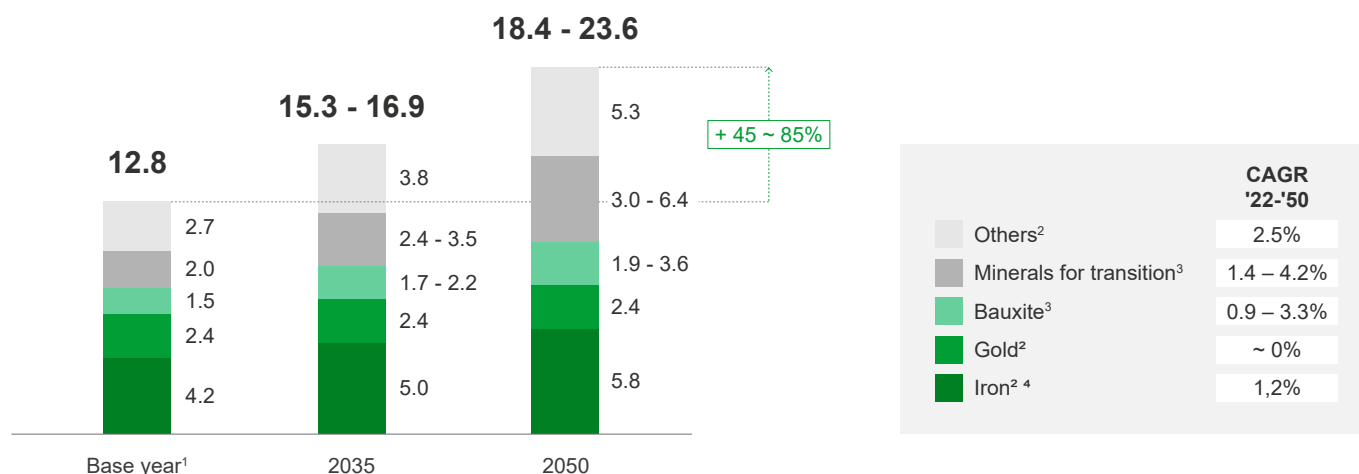
Evolution is not homogeneous among minerals. **Iron**, which accounts for most of the current emissions, shows moderate growth, with faster growth by 2035, reflecting growth rates equivalent to 1.2% per year in the 2022-2050 period. **Bauxite production** is likely to grow at a rate between 0.9% and 3.3% per year, while the other **minerals associated with the energy transition** could post faster expansions, ranging between 1.4% and 4.2% per year, depending on the scenario considered. **Gold** remains at a consistent production volume.

The projections were built from multiple sources, including the Studies for the National Mining Plan (PNM) 2050, other than data from the National Mining Agency, IBRAM, sustainability reports from companies in the sector and interviews with the Coalition. In the specific case of **minerals for energy transition**, the assumptions used are detailed in **Chapter 4 of this document**, allowing greater transparency on the demand for these inputs to global decarbonization.

It should also be noted that the study **only includes direct emissions from mining and beneficiation** aligned with the emissions inventory methodology of the sector developed by IBRAM, not including subsequent industrial processing steps for **chains other than iron**. As such, with the **expected expansion of Minerals production for the energy transition**, processing emissions (e.g., nickel, copper) are expected to **become increasingly important** and, if Brazil **advances in the industrialization** of these mineral chains (e.g., lithium, graphite), **a significant portion of this industrial activity could take place within the country**.

Such a perspective should not only be seen as a **climate challenge**, but especially as a **strategic opportunity for Brazil** to advance in its industrialization. By **expanding its mineral processing chains**, Brazil can trigger a **virtuous cycle of inclusive economic growth**, marked by higher value creation, greater productive diversity, and stronger international competitiveness. This movement has the potential to expand the industrial base, stimulate the training of skilled labor, attract investments in cutting-edge technology and ramp-up development in various regions. At the same time, this opportunity underscores the importance of **integrating decarbonization solutions** along supply chains, ensuring that industrial advancement aligns with climate goals.

Figure 4 – Emissions by ore (MtCO₂e) – Scenario of inaction



1. Considers base year 2022 2. The production forecasts align with the PNM growth rates, modified only by an adjustment to coal production to exclude canceled projects 3. Thirteen specific minerals were quantified—more details are available in the 'Minerals for the Energy Transition' chapter 4. An increase in emissions due to loss of operational efficiency of between 7%-24% was considered, in iron, bauxite, phosphate, tin and coal. **Sources:** Studies for PNM 2050; United States Geological Survey (USGS); IBRAM; International Energy Agency (IEA); Sustainability reports; Interviews with Coalition members

To address the challenge of rising emissions, it is important to build a decarbonization pathway that combines short-term actions with long-term structural solutions. This path is based on five groups of levers: replacing fossil fuels with lower-emission alternatives; the progressive electrification of fleets and the adoption of low-carbon hydrogen; increased efficiency and technological innovation; expanded use of renewable energy; and, finally, the restoration of areas as a neutralization mechanism.

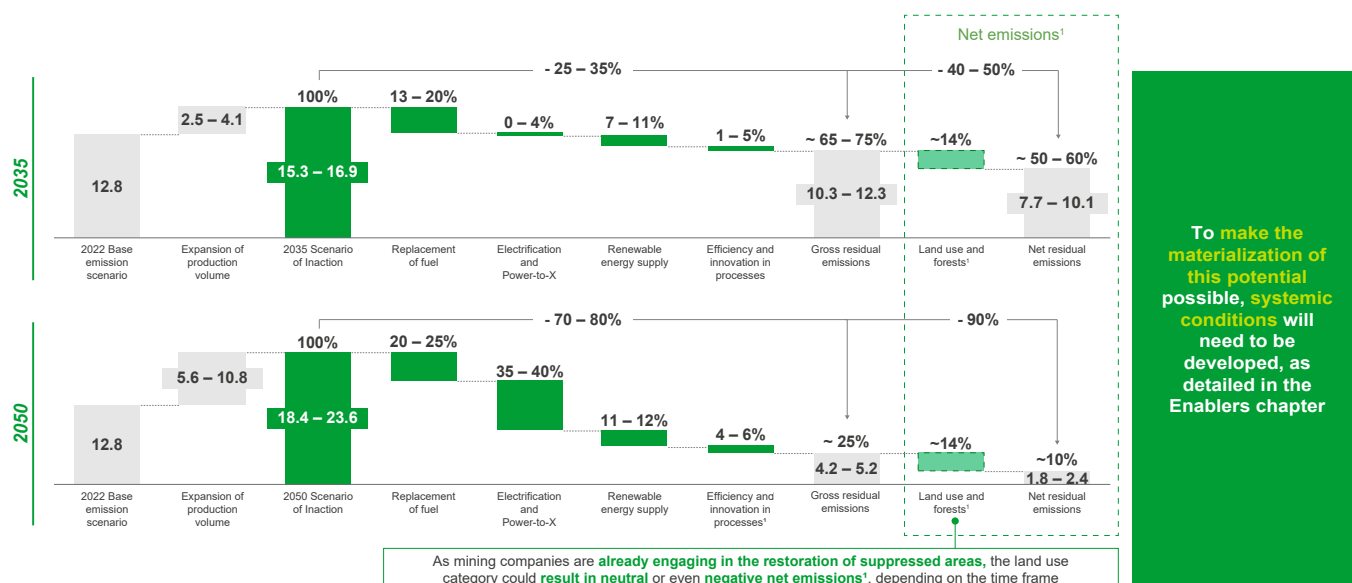
2.2 Mapping levers to reduce and predict the impact of contributions

Based on the estimates, the sector believes that there is a potential to reduce and neutralize about **40%-50% of its emissions by 2035** and up to **90% by 2050**, compared to the scenario of inaction. This potential stems from the combined adoption of different levers, with an emphasis on **replacing fossil fuels**, responsible for reducing emissions by about a quarter by 2050. Realizing this potential will depend on the **advancement of systemic enablers**, such as technology and R&D, infrastructure, financing, regulation, and value chain mechanisms that enable the scale adoption of the identified levers.

Electrification and power-to-X solutions have risen in importance over time, and can represent a reduction **of up to 40% of emissions in 2050**, as energy infrastructure advances and the costs of technologies fall. **Additional renewable energy and gains in process efficiency** are making significant, though smaller, contributions, enhancing the role of innovation in the sector's transformation.

Emissions from **land use and forests** represent a strategic dimension of decarbonization. Restoring suppressed areas, something mining companies are already doing, has the potential to generate neutral or even negative net emissions, depending on the time horizon of analysis. This factor emphasizes the role of nature-based solutions as an essential complement to industrial technologies, expanding the sector's ability to align productive growth with carbon neutrality.

Figure 5 – Emission reduction potential in 2035 and 2050 (MtCO₂e)



Notes: Emissions from coal production considered within the residual emissions block 1. Carbon removals achieved within company-owned and directly affected lands are deemed sufficient to neutralize land-use emissions. The current GHG Protocol methodology does not allow this approach to calculate net emissions, but accounting for sequestered carbon is an opportunity for miners' carbon neutrality goals.

Sources: IBRAM (Emissions Inventory), Coalition Discussions

Diesel substitution emerges as a key decarbonization lever for the mining sector, due to the high contribution of mobile combustion emissions, especially those linked to off-highway trucks. To reduce this dependence, it is important to understand which technological alternatives can enable the transition and which barriers still need to be overcome.

This substitution can occur through different paths, each with their own opportunities and challenges.

Figure 6 – Paths for fuel replacement, electrification and power-to-X

- 1 The **electrification of mining fleets** is expected to increase, particularly in those operations where the **energy demand** is not too high and where there is **adequate electrical infrastructure** in place
 - 2 Successful **large-scale electrification** necessitates a stable electrical grid, **robust chargers**, prudent battery management, and **established maintenance plans** for challenging environments. **Limited autonomy** and **recharge times** are still critical points for certain routes
 - 3 Conditions in Brazil are beneficial for the use of **biofuels** over the short- and medium-term: established **regulatory maturity**, a **well-developed production infrastructure**, the **potential for expansion**, and the ability to adapt **existing infrastructure to accommodate biofuel blends** with minimal modifications to existing engines
 - 4 **Hydrogen fuel cells** combine **long range** with **fast refueling**, but their potential depends on developing a cost-effective, **low-carbon hydrogen supply chain** and the necessary logistics and infrastructure in Brazil
- >>> The **attractiveness of the technologies** varies according to the profile of the site. **Electrification and trolleys** (electrification of trucks via electric cables suspended on ramps) are more advanced compared to **fuel cells**, which are still in the global testing phase. The decision requires integrated cost analysis, availability of the necessary technology and infrastructure

Drop-in biofuels (compatible with existing engines such as biodiesel and HVO) are expected to lead the transition up to **2035**. They require less investment, take advantage of the chain that has already been established in Brazil and can be used in existing engines with minimal adaptations, albeit with slightly higher maintenance costs than diesel.

The Transport Coalition has envisioned a situation where the use of renewable diesel blends is intensified over time, with the adoption of B25 by 2035 and B50 by 2050. These blends correspond to the mixture of fossil diesel with biofuels, like biodiesel and green diesel, with B25 indicating 25% renewable in the composition and B50, 50%. Increasing these levels can be achieved via regulatory adjustments, such as mandate increases, or through voluntary commitment to higher thresholds, subject to technical and economic viability. The mining sector is trending in this direction, with

pilots and discussions pointing to higher levels, such as tests on B25 in off-highway applications.

Pure electrification demands higher initial investments and faces autonomy constraints, but it tends to gain competitiveness as the cost of renewables falls and the energy density of batteries increases, especially in fixed-route mines. **Low-carbon hydrogen**, in turn, is expected to see slower adoption, restricted by production costs and a lack of adequate infrastructure, but with potential for expansion in the long term.

This perspective suggests that, by the middle of the next decade, biofuels will play a central role in the transition, while electrification and hydrogen are expected to gradually gain space over longer horizons, as technological advances and cost reduction make these routes more competitive.

Figure 7 – Feasibility and compatibility of technologies

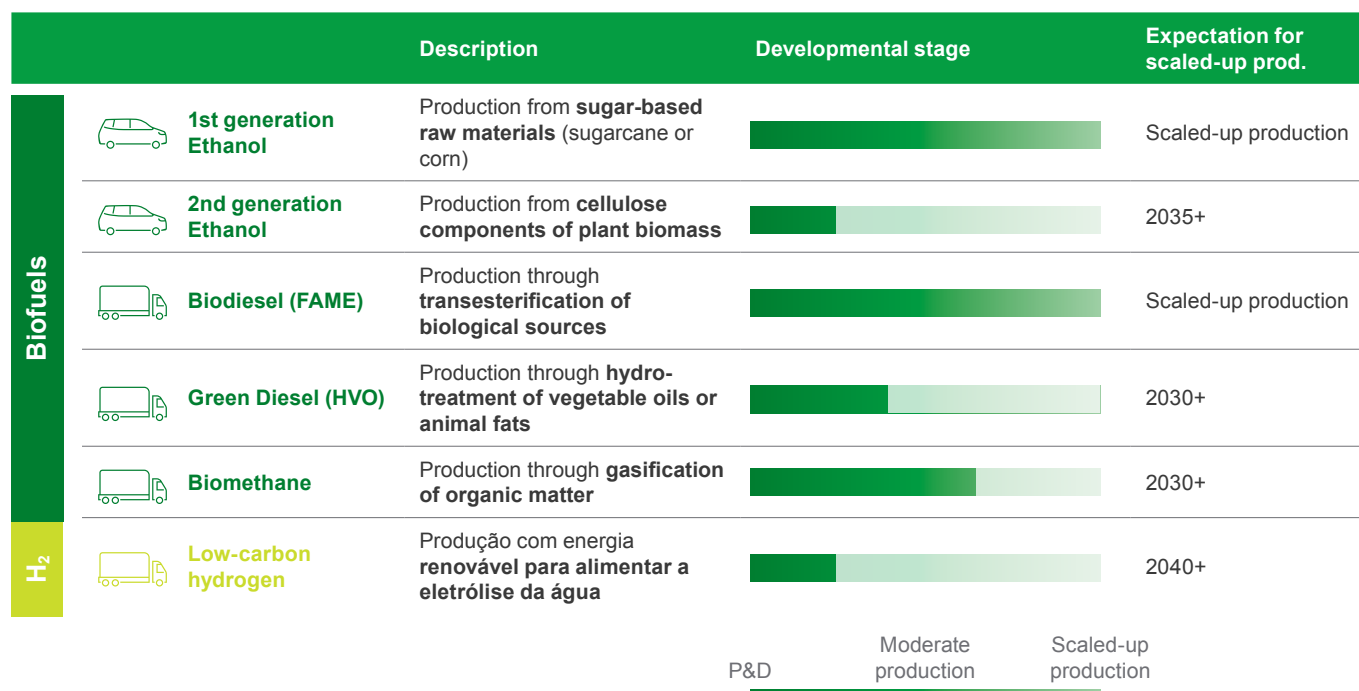
Technology	Technological and economic feasibility (2035)	Compatibility with mining use (2035)
 Biofuels (Biodiesel and HVO)	 • Reduced CAPEX in infrastructure (existing tanks and pumps, adjustments in seals and hoses for drop-ins) • Strong and adaptable Brazilian supply chain capable of handling potential supply limitations by using flexible blending options • Possibility of reducing the cost of HVO with scale-up	 • Allows use of the same powertrain with minimal sealing/injection adaptations (HVO, biodiesel) • Fast supply, maintaining operational availability • Increased maintenance costs compared to diesel
 Battery only	 • Requires high CAPEX for new infrastructure • Pure battery becomes competitive with diesel as renewables costs plummet and maintenance is reduced • Greater feasibility in mines with fixed haul routes and/or integration with trolley assist systems	 • Requires large, heavy battery to address power demands and usage patterns • Smaller battery is possible with frequent recharges, but this can hinder continuous operation • For mass electrification in 2050, energy density needs to be improved
 H ₂ Fuel Cell	 • Currently not feasible due to high H₂ cost • Low-carbon H₂ supply challenge • Expected medium-term economic maturity and competitiveness • OPEX depends on costs of renewable energy dropping	 • Em teoria, melhor se adapta ao padrão de uso (reabastecimento rápido reduz paradas) e atende requisitos de alta potência

Note: HVO: Hydrotreated Vegetable Oil, also known as Green Diesel. On the international stage, Biomethane, Bio-CNG and Bio-LNG face supply limitations, mainly due to the absence of structured international trade and infrastructure restrictions in certain regions. E-fuels, on the other hand, are still in the pilot phase—although the first commercial production is expected in 2030, large-scale adoption is unlikely to occur before 2040 due to technological challenges. In Brazil, Vale has announced a partnership to develop an ethanol engine.

Source: Documentary research, Coalition debates

Brazil has certain advantages that aid in facilitating the decarbonization process. Brazil already relies on scaled and mature solutions, including **first-generation ethanol, biodiesel, and HVO**. It also has expanding technologies, such as **second-generation ethanol, biomethane, and advanced green diesel**, that are expected to become highly relevant over the next decade. **Low-carbon hydrogen**, while promising, is only expected to achieve large-scale competitiveness after 2040 in light of cost and infrastructure challenges.

Figure 8 – Evolution of biofuels in Brazil represents an alternative to decarbonization and electrification



Note: FAME (Fatty Acid Methyl Esters) is a type of biodiesel produced from vegetable oils or animal fats.

Source: Unleashing Brazil's Low-Carbon Hydrogen Potential, documentary research

This outlook highlights a likely trajectory: **biofuels support the short-term transition, electrification gradually becomes established, and hydrogen completes the energy portfolio in the long term.** Based on this, the country is uniquely positioned to align its mining with the global climate agenda.

2.2.1 Replacement of fuels

Figure 9 – Levers - Replacement of fuels

Levers	Current feasibility analysis	References
1 Increase in the partial replacement of diesel with biofuels in the fleet without the need for major engine modifications (drop-in – B12 > B25/B30) ^{1 3 4}	 Commercially available. However, it faces logistical barriers such as maintaining a stable supply and storage	B25 tests in Vale's fleet
2 Adoption of biofuels in the fleet , with total or partial replacement of diesel by higher proportion blends ²	 Technically feasible; requires OEM compatibility/warranty or retrofit of components. Higher fuel cost; segregated supply logistics	Totally replacing fuel for biodiesel in heavy machinery at Rio Tinto's Boron operation
3 Increase in the partial replacement of diesel with biofuels in stationary combustion equipment without the need for major engine modifications (drop-in – B12 > B25/B30) ^{3 4}	 Commercially available; modern stationary equipment already accepts B20 without alteration. Mixtures above may require some minor adjustments to components (gaskets and hoses)	Cat diesel generators can run on biofuels and have accommodated the use of biodiesel and HVO for over a decade Cummins releases a list of engine models approved for B20 use
4 Adoption of biofuels in stationary combustion equipment, with total or partial replacement of diesel by higher proportion blends ²	 Technically feasible; requires lightweight compatibility and/or retrofit of stationary motors. Higher fuel cost; segregated supply logistics	Use of 100% palm biodiesel (B100) in BBF stationary generators in thermoelectric plants in the Amazon

Notes: 1. B12, B25, B30 represent blends of 12%, 25% and 30% biodiesel to fossil diesel. 2. Includes biodiesel, HVO, biomethane and ethanol 3. Considers mandatory legal addition of B25 due to the Fuel of the Future Law, plus voluntary additions of 5 p.p. in the suggested adoption rate. B12 was considered based on the 2022 reference year 4. Blend of the future B30 includes biodiesel (FAME) and green diesel (HVO)

2.2.2 Electrification and power-to-X

Figure 10 – Levers – Electrification and power-to-X

Levers	Current feasibility analysis	References
1 Implement electric shovels and LHDs to replace diesel alternatives with cleaner solutions	 Moderate viability, dependent on electrical infrastructure in the pit	Newmont – Borden underground mine (Canada) "all-electric" with reduced ventilation and emissions BHP's Escondida mine in Chile – use of electric cable shovel
2 Deploy trolley assist technology in haulage operations, enabling trucks to draw power from overhead lines during ascents and thereby reduce diesel dependency on inclined routes	 Viable on defined ramps; requires construction of contact overhead lines and adaptation of the fleet, which implies significant initial investment	First Quantum Kansanshi, Sentinel and Panama Copper mines operating with trolley assist
3 Implement battery-powered trucks (BEV) to replace diesel alternatives	 Moderate viability, dependent on electrical infrastructure in the pit; prototypes under test	Collaboration between Rio Tinto and BHP in testing large battery electric haulage truck technology in Pilbara, Western Australia
4 Implementing off-road FCEV¹ trucks to replace diesel vehicles with hydrogen fuel cell alternatives	 Advanced prototype; requires electrolyzer (local production)/guarantee of H ₂ supply; potentially high costs	Anglo American – Mogalakwena (South Africa), since May 2022 Fortescue – Pilbara (Australia) – Prototype H ₂ being tested at Christmas Creek since August 2024

1. Fuel Cell Electric Vehicle

Electrification and hydrogen: opportunity of up to R\$94 billion in investments by 2050

The electrification of off-highway truck fleets and equipment such as shovels and LHDs, along with the adoption of power-to-X solutions in Brazil, represents an investment opportunity of approximately R\$77 to R\$94 billion—capable of transforming mining logistics and attracting capital toward low-carbon technologies.

The estimate considers the **four levers together**: electric shovels and LHDs, battery-powered trucks (BEV)¹, fuel cell trucks (FCEV)² and trolley assist systems for trucks on ramps³, in a **scenario of gradual growth in the adoption of these technologies**, supported by advances in infrastructure, financing and technological development that allow their large-scale implementation. These values give the dimension of the scale of resources that will be necessary to enable the electrification and use of hydrogen in mining, consolidating this lever as one of the most transformational in the decarbonization agenda

1. Average cost of R\$41 million per electric truck (premise adopted by IBRAM in the Technical Report on the Construction and Analysis of the Marginal Cost of Mining Abatement Curve) and R\$10 million per LHD. 2. Eight 100 kW cells per FCEV truck, with unit values ranging between US\$190 and US\$2,200 per kW. 3. Investment of R\$80.5 million for a 2 km system (premise adopted by IBRAM in the same document)

2.2.3 Renewable energy

Figure 11 – Levers – Renewable energy

Levers	Current feasibility analysis	References
1 Implement solar and wind PPAs to eliminate scope 2 and foster electromobility	 Highly feasible in Brazil due to maturity of PPAs contracts – can be deployed quickly	Vale: Sol do Cerrado solar complex supplying ~16% of the company's demand in the country with a reduction of ~134 kt CO ₂ per year CBA: installed capacity to generate 100% renewable electricity through 21 hydroelectric power plants and 2 wind farms
2 Implement on-site PV solar (ground-mounted or rooftop) to utilize unassigned areas and provide a partial energy supply for the facility	 High viability and fast payback	Rio Tinto (AUS): Iron ore mine Gudai-Darri with 34 MW of solar energy installed

Note: PPAs (Power Purchase Agreements) are long-term energy purchase and sale agreements.

2.2.4 Efficiency and innovation in processes

Figure 12 – Levers – Efficiency and innovation in processes

Levers	Current feasibility analysis	References
1 Increase route efficiency (scanning, telemetry and sequencing) and vehicle efficiency (LRR tires and engines) to reduce diesel consumption	 Available software and technologies; low investment	Use of AI-integrated digital twins for sequencing of activities and routes by BHP Use of telemetry data for route optimization by Rio Tinto Michelin: "Energy Efficiency Tires" with lower rolling resistance reducing consumption by up to 5%
2 Optimize crushing and grinding equipment for enhanced energy efficiency	 Available software; low investment	Calibrated mathematical models for drilling, blasting, primary gyratory crushing, and SAG/Ball milling at Compañía Minera Antamina
3 Use of conveyor belts to replace part of the transport done by trucks	 Mature technology; high impact on CO ₂ e cost, but requires civil work and layout redesign	Vale S11D <i>truckless</i> system with ~70 km

Note: LRR tires are Low Rolling Resistance tires designed to reduce energy loss during rotation

2.2.5 Land use and forests

Emissions associated with land use are an important issue for the decarbonization of mining. The sector's activities in Brazil **are subject to legal conditions that determine mandatory environmental and forestry compensation**. Federal and state rules now **require companies to implement compensation measures**, as provided for in Degraded Area Recovery Programs (PRAD) and Mine Closure Plans (PFM).

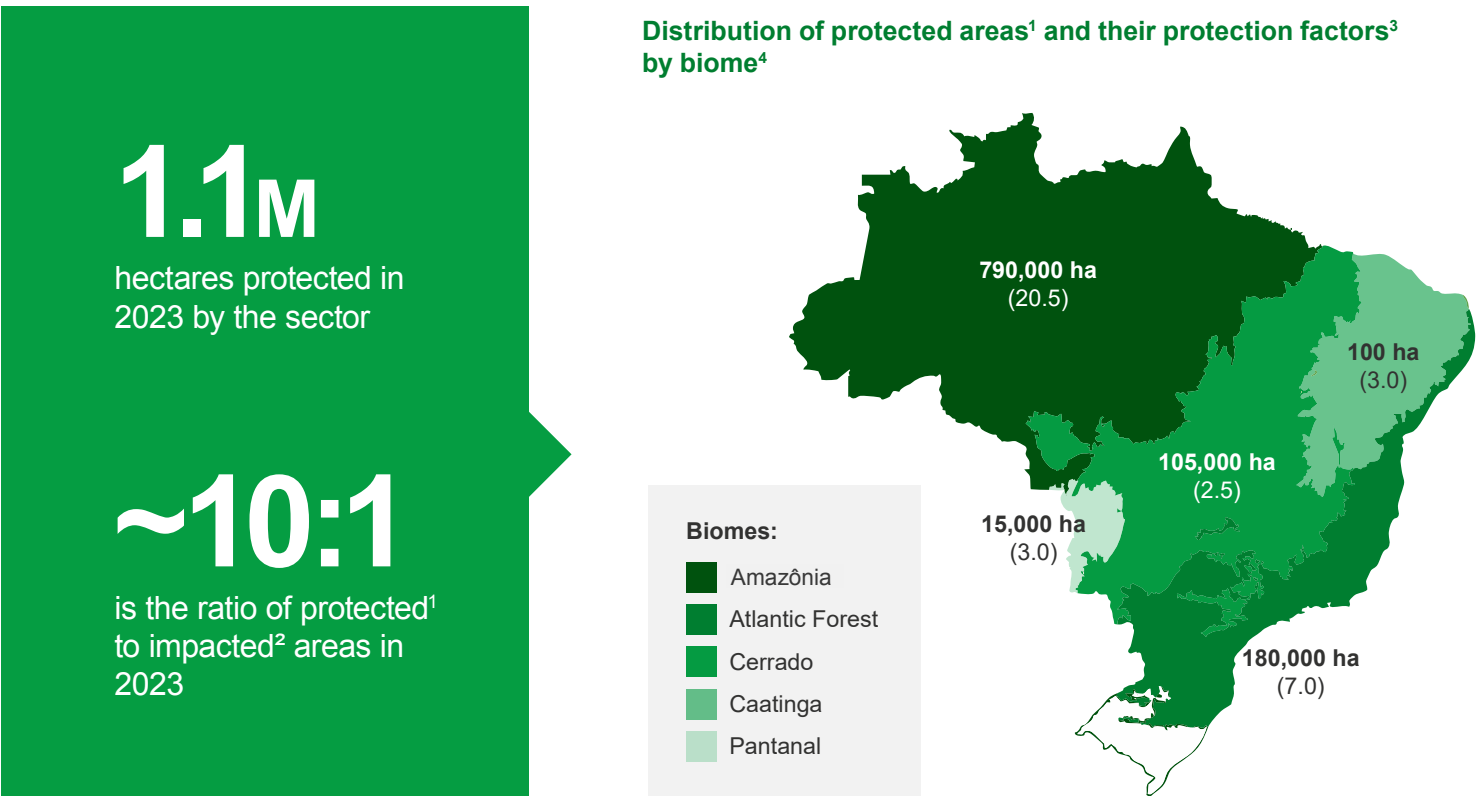
In addition to these legal requirements, mining companies have **an additional opportunity to neutralize emissions** that can be exploited through voluntary actions. These initiatives go beyond regulatory obligations, allowing mining companies to expand their positive impacts, generating additional

environmental benefits and serving as leverage to support emission neutrality goals in the sector.

In addition to the recovery of areas, mining companies also contribute to combating deforestation by protecting areas: **in 2023, mining companies preserved more than 1 million hectares of native vegetation**.

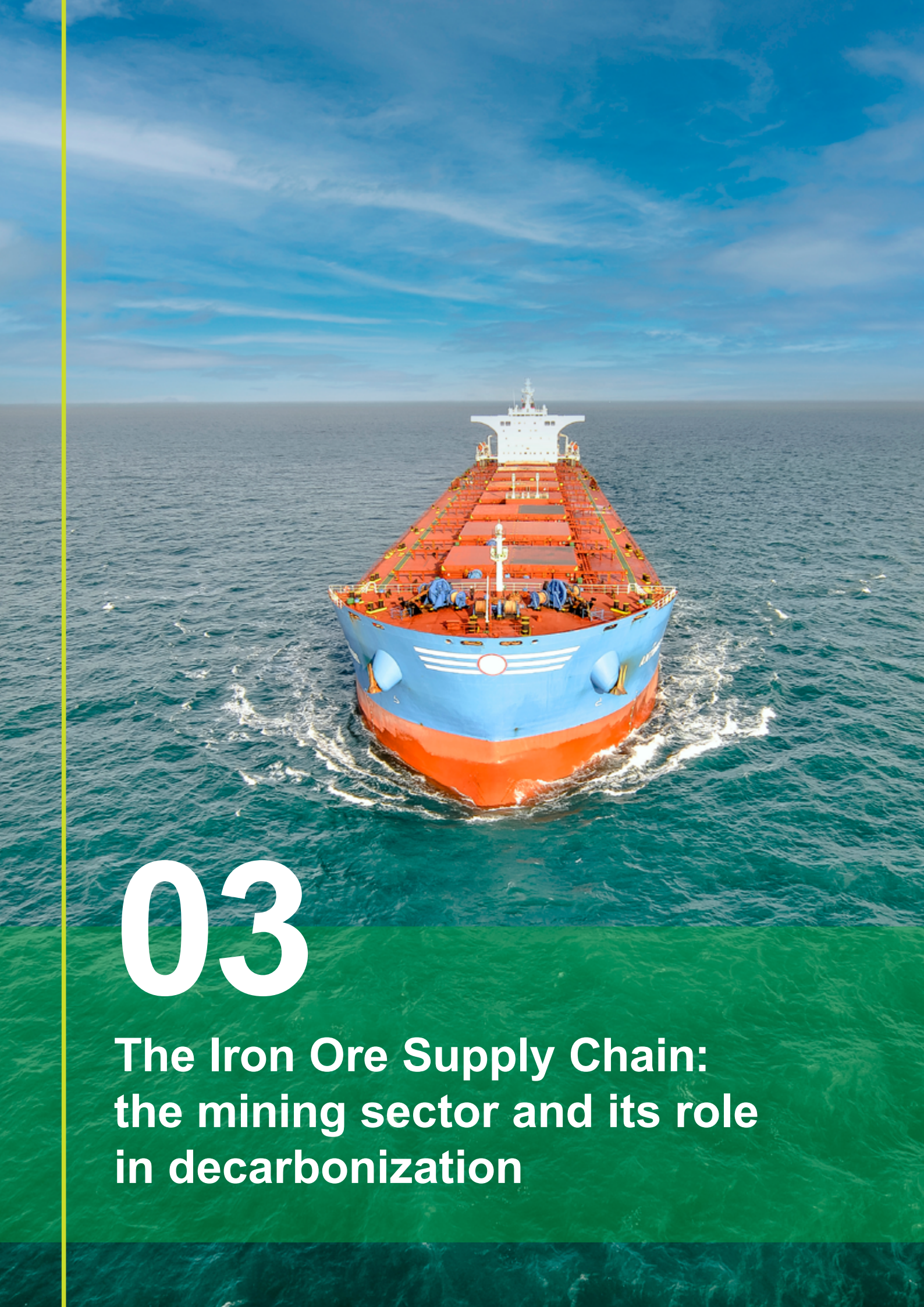
Despite the potential for impact, the use of neutralization solutions to achieve mining companies' reduction targets is something that has yet to be addressed by international methodologies. This theme is explored in more depth in the *Enablers* chapter.

Figure 13 – Restoration and protection of lands in Brazil by the mining sector



1. Geographically defined area that is designated, regulated or managed to achieve specific preservation objectives, including Permanent Preservation Areas (PPAs) and Legal Reserves. 2. Geographical area where the mining and support structures are located, including internal access routes that will undergo physical and biological changes resulting from the implementation and operation of the project. 3. List of protected areas by impacted areas. 4. Approximation calculated from the percentage by state of each biome together with IBRAM data by state.

Sources: Results from the Brazil Mining ESG Agenda 2024, IBRAM; MapBiomas

A large blue and orange iron ore ship is sailing on the ocean under a blue sky. The ship is viewed from a high angle, showing its deck and superstructure. The water is a deep blue-green, and the sky is a clear blue with some light clouds. The ship's hull is orange, and its superstructure is blue. It has a white funnel with a red circle and three white stripes. The ship is moving towards the horizon, leaving a white wake behind it.

03

**The Iron Ore Supply Chain:
the mining sector and its role
in decarbonization**

Decarbonizing the iron ore supply chain requires a multi-angle analysis, taking into account the degree of control and influence held by mining companies across different stages. The sector can contribute in four key ways: (1) by providing **low-carbon inputs to steelmaking**, such as DR-grade¹ pellets and briquettes; (2) by collaborating with strategic suppliers to **reduce emissions in long-distance shipping**; (3) by decarbonizing **associated industrial steps, such as pelletizing**; and (4) by reducing **logistics emissions linked to rail transport**.

Taken together, these aspects can represent a significant contribution: in 2050, thanks **to the advancement of systemic conditions and the acceleration of the energy transition**, Brazilian mining can help **to enable reductions of 100 to 110 MtCO₂e along the iron ore chain**.

Scaling up Brazil's output of DR-grade pellets and briquettes may enable part of the inputs required for the global transition of steelmaking from integrated routes (BF-BOF²) to direct reduction technologies. The potential is around **80 MtCO₂e in 2050**, highlighting Brazil's strategic role as a global supplier of inputs for low-carbon steel.

The export of Brazilian ore is associated with significant emissions from long-haul shipping. By collaborating with shipowners and fuel suppliers to accelerate the adoption of low-carbon solutions, mining can be a contributor to the goals of the International Maritime Organization (IMO) with reductions of **15 to 25 MtCO₂e in 2050**, depending on the growth of exported volume and also on the definition of the target of residual emissions for the period.

The pelletizing process also offers space for decarbonization through fuel substitution, energy efficiency, use of renewable electricity, and process innovations. The reduction potential was estimated at **4 to 5 MtCO₂e in 2050**, reducing the intensity of this fundamental operation for the steel chain.

Lastly, the rail transport of iron ore represents a relevant part of the emissions of this modal. The application of levers such as operational efficiency, biofuels and partial electrification can reduce up to **1 to 2 MtCO₂e in 2050**, contributing to cleaner and more efficient logistics.

Figure 14 – Contribution opportunities along the iron chain



1. DR-grade (Direct Reduction grade) refers to forms of processed iron ore (such as pellets or briquettes) with characteristics suitable for use in direct reduction processes 2. Blast Furnace – Basic Oxygen Furnace, an integrated steel production route in which iron ore is reduced in a blast furnace (BF) and then converted to liquid steel in a basic oxygen converter (BOF).

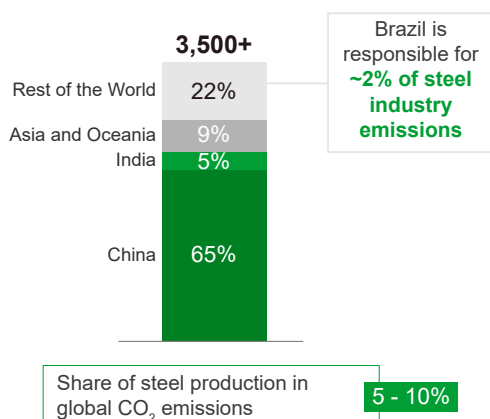
3.1 Expansion of inputs for low-carbon steel production

The steel industry is responsible for a significant share of global emissions, representing around 5% to 10% of total world emissions in recent years.

Figure 15 – Steel emissions and factors for its decarbonization

Emissions from the steel industry are significant and concentrated in Asia

Global emissions from steel production MtCO_{2e}



Decarbonization depends on three pillars



Available technology

The technology needs to be mature and affordable in order to be implemented at scale



Financial viability

The alternative needs to be financially viable considering current carbon pricing



Suitable inputs

Appropriate raw materials provided by mining and structured supply chain (GN, H₂ and scrap) are required

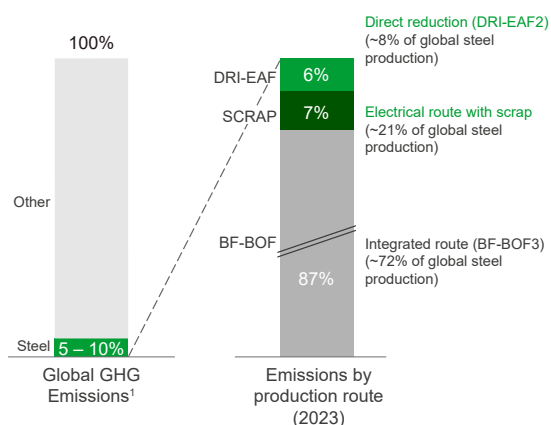
Source: Global Financial Markets Association (GFMA) and BCG: Climate Finance Markets and the Real Economy

Much of this **impact stems from the traditional integrated route, or BF-BOF** (blast furnace and oxygen converter), which accounts for about 70% of global steel production and almost 90% of the sector's emissions. The **transition to direct reduction (DR) routes, using natural gas and low-carbon hydrogen**, is key to reducing the carbon footprint of steel, but **depends on multiple factors**, including technology, financial viability and adequate inputs.

The direct reduction process, although less emitter, has higher purity requirements for the iron ore used. Currently, a small portion of world production meets the requirements for direct reduction routes (DR-grade), which is another challenge for the decarbonization of steel.

Figure 17 – Supply challenge: high-quality and low-cost ore for DR routes

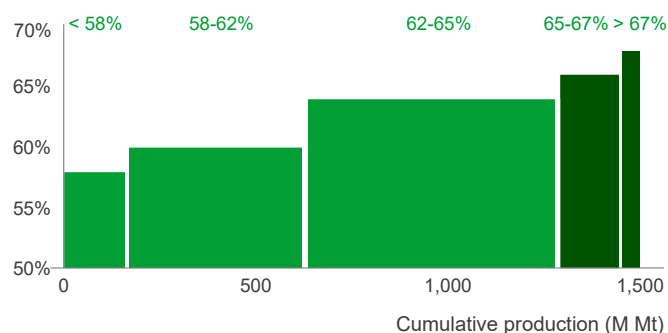
Figure 16 – Steel emissions by route



1. Greenhouse Gases 2. Direct Reduction Iron - Electric Arch Furnace – direct reduction route, without auto furnace stage, which requires DR-grade inputs and has reduced emissions compared to the BF-BOF route 3. Blast Furnace – Basic Oxygen Furnace, an integrated steel production route in which iron ore is reduced in a blast furnace (BF) and then converted to liquid steel in a basic oxygen converter (BOF).

Source: World Steel Association

Global ore production by % Iron content



Note: The Simandou (Rio Tinto) project, with an iron content comparable to that of Carajás (65%-68%), is expected to start operating in the coming years, expanding the global supply of DR-grade

Source: Institute for Energy Economics and Financial Analysis: Iron Ore Quality a Potential Headwind to Green Steelmaking (June 2022)

Direct reduction processes **rely not only on high-grade ore, but also on competitively priced inputs such as natural gas and clean energy for hydrogen generation**. As a way to optimize access to required resources and the subsequent transportation to consumer centers, the steel industry has collaborated with mining companies and energy producers to build integrated **hubs connecting mineral resources, competitive energy vectors and consumer centers**.

1 Hubs are strategic levers to accelerate the green steel transition

They help to reconfigure the global value chain of the steel industry

They concentrate assets seeking the best combination between:

- Access to iron ore
- Access to natural gas and/or low-carbon hydrogen
- Proximity to major consumer centers

They enable the search for the best technical-economic combination

2 Execution depends on a robust collaborative ecosystem

Alignment between mining companies, energy producers, investors, governments and customers

Efficient and integrated logistics coordination

Long-term contracts that ensure economic viability

Public policies that encourage investments and innovation

3 Brazil is strategically positioned to lead

High-grade iron ore and pelletizing capacity

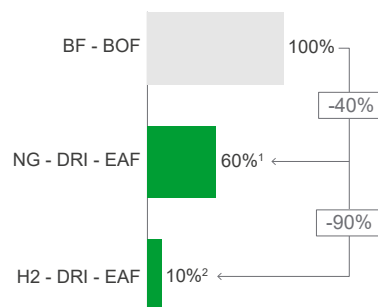
Competitive access to renewable energy sources

Existing logistics infrastructure (ports, railways)

Potential to attract international investments and consolidate integrated hubs

In this context, **Brazilian mining can play a strategic role** with its high-grade iron ore reserves, capable of feeding direct reduction routes that have reduced emissions compared to the integrated route. While steel production by the integrated BF-BOF route emits, on average, 2.32 tCO₂e per ton, the natural gas-based DR route can reduce these emissions by about 40% and the hydrogen DR route by up to 90%.

Figure 18 – Emissions vs. BF-BOF route



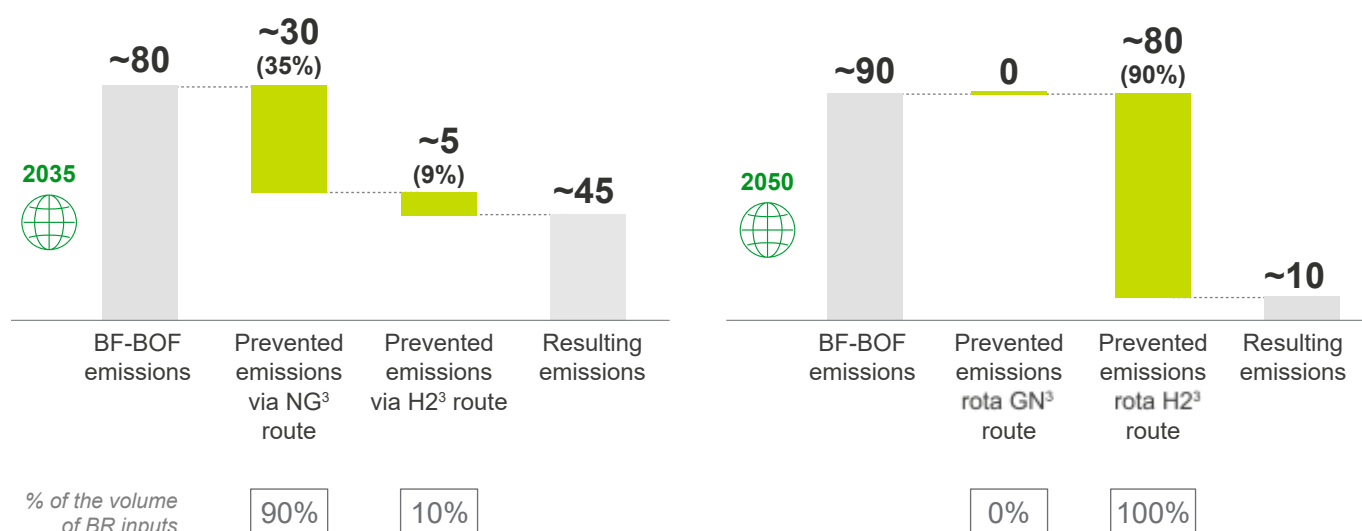
1. Considers current emission factors from the Sustainability Indicators 2024 report 2. Considers electricity from renewable sources
Source: World Steel Association; Midrex

The evolution of the mix of technological routes by 2050 will play a central role in the decarbonization of the global steel industry. This study projects that, by 2035, most of Brazil's DR-grade inputs will be allocated to natural gas-based direct reduction (90%), with hydrogen-based reduction accounting for an initial 10% share. By 2050, the situation will have evolved into a more ambitious one, with 100% of Brazilian resources being directed towards low-carbon hydrogen pathways, enabling a significant reduction in emissions from global steel production.

In volume terms, Brazil's supply is estimated to reach **45 Mton of DR-grade inputs by 2035**, a level sufficient to enable the production of approximately **35 Mton of steel globally** through direct reduction routes. If this same volume were produced by the traditional integrated route (BF-BOF), the associated emissions would be around 80 MtCO₂e. Considering the projected mix—with 90% of production via natural gas and 10% via hydrogen—emissions are expected to be 45 MtCO₂e, resulting in a **reduction of 35 MtCO₂e globally**.

By 2050, the potential expands. It's projected that Brazil can supply **50 million tons of DR-grade inputs**, enabling about **40 million tons of steel globally** on routes totally based on low-carbon hydrogen. In this case, production via the BF-BOF route would generate emissions on the order of **90 MtCO₂e**, while the full adoption of the hydrogen route would reduce this value to **10 MtCO₂e**, representing a **reduction of approximately 80 MtCO₂e globally**.

Figure 19 – Global reduction of emissions enabled by Brazilian DR-grade inputs (comparison between DR vs. BF-BOF routes, MtCO₂e)



1. Projection considers an increase in pelletizing volume reaching the capacity of 26.4 Mton for Samarco (2Q2025 Investor Report) before 2035. After 2035, there is no growth of pellet capacity. Briquettes grow from 2.2 Mton in 2024 to 10 Mton in 2035 and 21 Mton in 2050, assuming proportional growth in the period. Considers a 50% mix of DR-grade inputs for Vale and 60% for Samarco. 2. A factor of 1.46 is considered for the ratio of metallic charge fed into the furnace, and a factor of 0.92 is used for the ratio of DR fed into the EAF. 3. A baseline of 2.32 tCO₂/t of steel is considered for the BF-BOF route, with projected reductions of ~40% for natural gas (NG) route and ~90% for the H₂ route, assuming that no DR-grade inputs are diverted to BF-BOF operations. Considers electricity from renewable sources for H₂.

Sources: Sustainability reports; Interviews with Coalition members; World Steel Association; Midrex.

As previously stated, securing DR-grade inputs at competitive prices and suitable volumes is just one complex hurdle the steel industry must overcome for decarbonization. This journey requires its own set of systemic enablers and the modification of global supply chains well outside the scope of mining. The effective use of these inputs in low-carbon routes **will depend on the development of steelmaking capacity in the world to process them** according to the technological requirements of the DR routes, which will involve **large investments**. Additionally, this expansion will require **adequate incentives and enablers for the steel industry**, which will need to balance the growing demand for low-carbon steel with its investment capacity and limitations of the existing industrial park, composed of long-life assets.

Figure 20 – Levers of the iron ore chain – Products for the steelmaking

Levers	Current feasibility analysis	References
1 Upgrade or scale existing pelletizing facilities to supply DR-grade pellets —critical for supporting DRI-EAF routes using natural gas or green hydrogen	Installed know-how, low technical risk; dependent on the availability of ores with high iron content and controlled contents of contaminants such as phosphorus and alumina	Samarco DR-grade pellet production Vale plants in Oman
2 Apply cold agglomeration for briquette formation , converting iron ore fines into briquettes without the need for sintering or pelletizing, enabling use in DR routes or as partial feed in blast furnaces	Plants in operation; tests being carried out in the steel industry	Vale plant in Tubarão

3.2 Collaboration with suppliers in long-haul shipping

Long-haul shipping, responsible for a relevant portion of emissions involving the export of Brazilian ore, enters a new cycle of regulatory transformation. The **International Maritime Organization (IMO) Net Zero Framework**, approved in 2025 and scheduled to become effective in 2027, still subject to formal adoption, establishes a global regulation aimed at achieving net-zero emissions by 2050 in international shipping.

This mechanism creates a sectoral carbon pricing system, in which non-compliant ships must purchase remediation credits or pay fines, while vessels that comply with the limits will receive negotiable credits. Plus, an international fund will collect resources from penalties to reinvest in sustainable technologies and solutions for the sector.

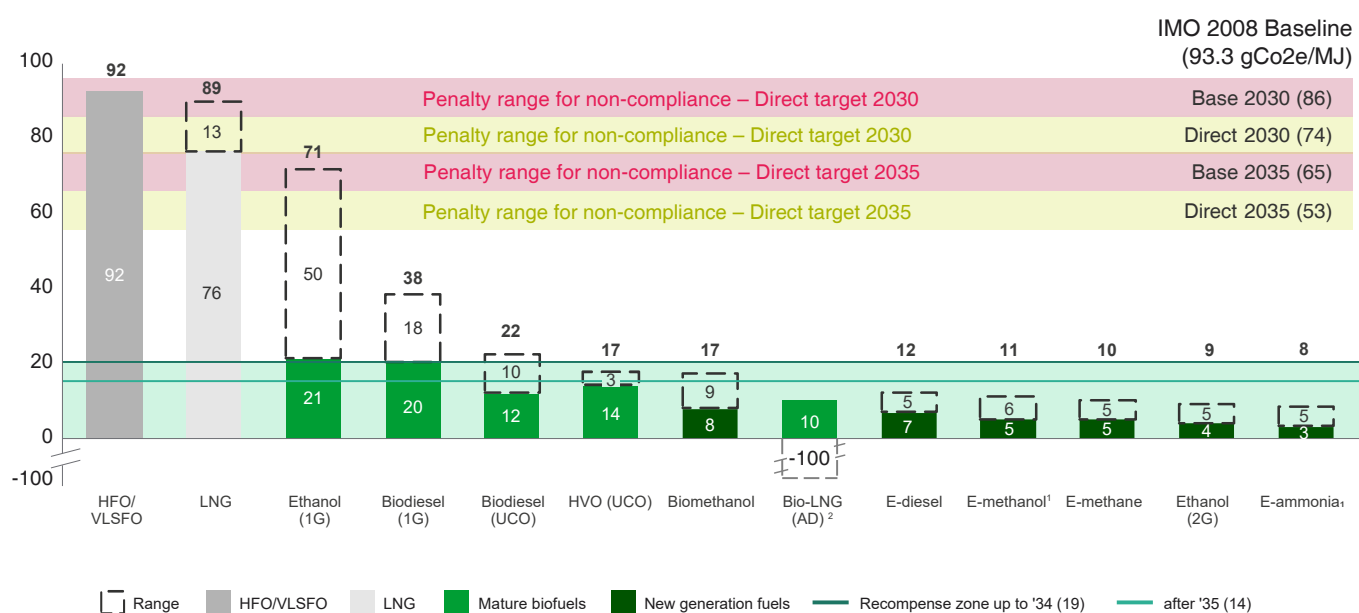
The implication is clear: over the next few decades, **only low-carbon fuels will be able to meet regulatory requirements**. This should accelerate the development and adoption of alternatives such as advanced biofuels, green methanol, ammonia and

hydrogen, while opening new market opportunities for suppliers capable of ensuring a stable flow of these inputs.

In this scenario, **mining plays an indirect but important role** in collaborating with shipowners and suppliers to enable low-carbon navigation solutions, reinforcing the alignment of the Brazilian ore logistics chain with global climate goals.

The export of Brazilian iron ore associated with long-haul shipping has estimated emissions between 15 and 20 MtCO₂e in 2022. This volume can be reduced substantially with the combination of **energy efficiency and adoption of low-carbon fuels**. The role of mining, as such, **is to collaborate with suppliers and shipowners**, signaling the importance of the energy transition in the seaborne freight market and supporting the development of solutions at scale. The potential reduction is significant and will depend on definitions in the IMO regulation on the target of residual emissions to be pursued by the sector.

Figure 21 – GHG intensity between fuels (WTW in gCO₂e/MJ)

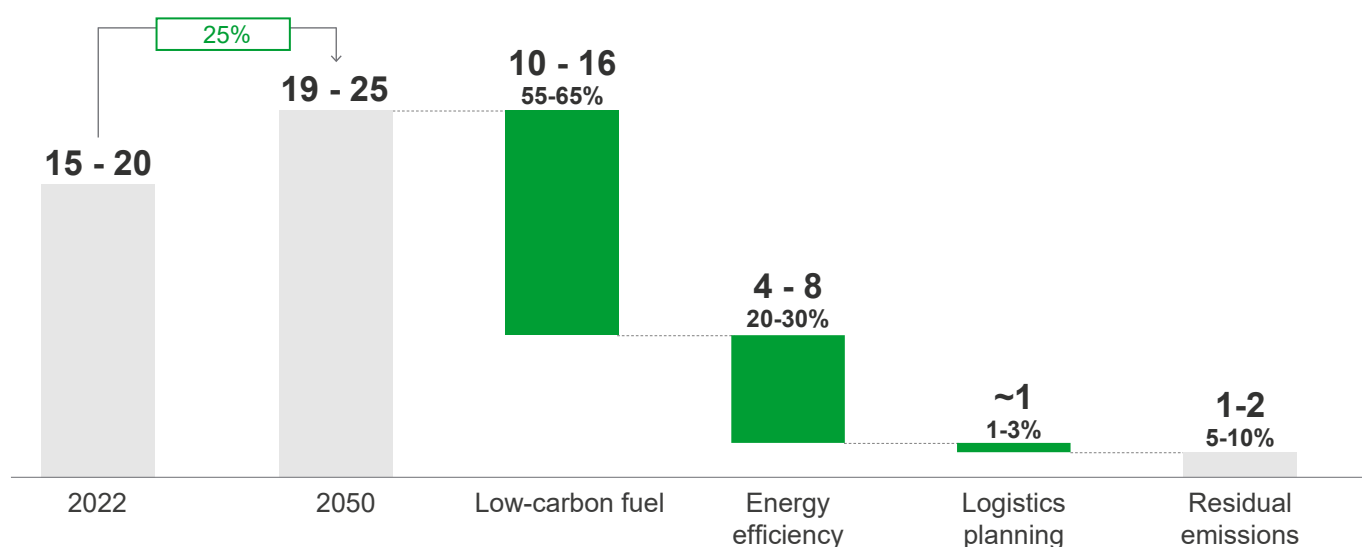


Notes: The list of fuels in the chart is not exhaustive; HFO/VLSFO: Heavy Fuel Oil/Very Low Sulphur Fuel Oil; LNG: Liquefied Natural Gas; UCO: Used Cooking Oil; HVO (UCO): Hydrotreated Vegetable Oil obtained from waste oils, such as used cooking oil; Bio-LNG (AD): liquefied biogas (bio-methane LNG), obtained via Anaerobic Digestion of organic waste.

1. Pilot flame emissions for ammonia or methanol were excluded from this analysis. While the impact is typically low when biofuels are used, it can substantially raise carbon intensity if fossil fuels are employed (potentially accounting for up to 13% of HFO demand) 2. In the case of anaerobic digestion, the carbon index may vary according to the raw material used.

Sources: Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping; IMO – MEPC 83; Global Centre for Maritime Decarbonisation (GCMD); FuelEU Maritime; Argus; International Energy Agency (IEA)

Figure 22 – Long-haul shipping emissions of iron ore export from Brazil – 2050 (MtCO₂e)



Notes: Estimate based on Vale's emissions, considering its share of exports proportional to its share of iron ore production. Considers that the volume of exports follows the growth of iron ore production in Brazil. Considers IMO Net-Zero emissions target in 2050—this target has yet to be defined by the IMO and could result in residual emissions different from those projected.

Sources: Vale; International Maritime Organization (IMO); DNV – Maritime forecast to 2050

Figure 23 – Levers of the iron ore chain – Long-distance shipping

Levers	Current feasibility analysis	References
1 Prioritize charter contracts that require the use of dual-fuel ships (LNG, methanol, ammonia) or vessels powered by low-carbon fuel (biodiesel, ethanol) , enabling the fleet's energy transition	 Available technology (dual-fuel); dedicated vessels depend on new investments and long-term contracts	Vale conducting tests with B24 through the Ecoshipping program BHP to launch five Newcastlemax dual-fuel LNG bulk carriers in 2020 Anglo American with ten Capesize+ dual-fuel LNG bulk carriers
2 Prioritize contracts that require energy efficiency systems on ships such as slow steaming, anti-friction coatings, use of sails, etc.	 Available technologies; investments range from moderate (painting) to high (rotor sail); depend on route profile	Use of rotating sails on a MOL ship for operation by Vale Use of silicone-based coatings on Vale's Liwa Max ship Use of inflatable sails, like the WISAMO model developed by Michelin
3 Implement integrated logistics planning (port-mine-ship) , reducing port waiting time , increasing ship occupancy rates , backhauling percentage and avoiding suboptimal departures	 Operational technology in use; depends on integration between systems, in addition to coordination between planning and operations areas	Vale, BHP and Rio Tinto with Integrated Operations Centers to adjust logistics planning and optimize shipments

Sources: National Challenges and Trajectories for Marine Fuels (EPE); Caprace, J.-D. et al. Sustainable Shipping: Modeling Technological Pathways Toward Net-Zero Emissions in Maritime Transport (Part I) - Sustainability, 2025

3.3 Decarbonization of the pelletizing stage

The pelletizing process is currently responsible for estimated emissions of between 2.5 and 3.5 MtCO₂e, and these emissions are projected to increase to between 4.5 and 5.5 million metric tons by the year 2035, assuming production expands.

Several levers can reduce these emissions, including the use of **charcoal, biofuels, renewable electricity and process innovation**.

By 2035, replacing fossil fuels could **reduce emissions by up to 15%**. By 2050, **reductions close to 90%** were assessed, equivalent to 4-5 MtCO₂e. Realizing these projections **will depend on innovating processes and technologies that are currently not fully developed**, such as low-carbon hydrogen, or on **significantly expanding the production and distribution of biofuels and biomass**. As detailed in the *Enablers* chapter, the advancement of these solutions will depend on technology, infrastructure, regulation, financing requirements, among others.

Figure 24 – Emission Baseline – 2035 and 2050 (MtCO₂e)

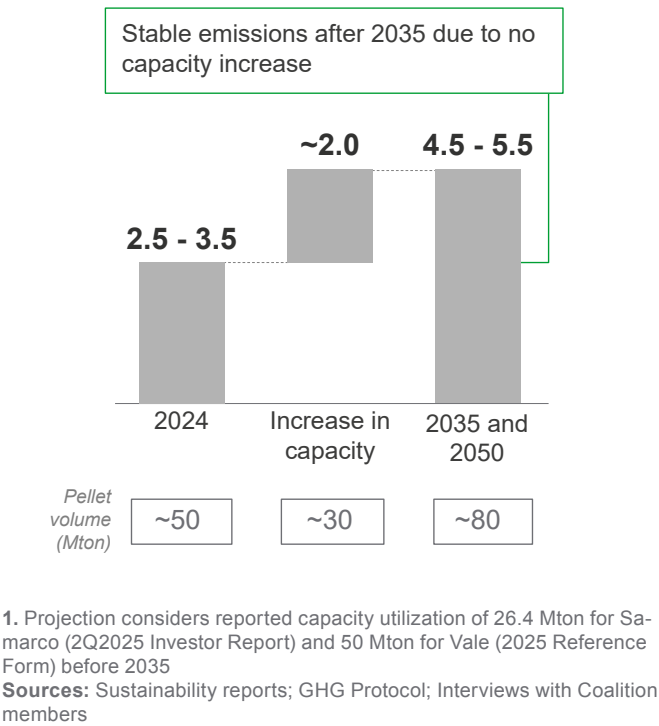
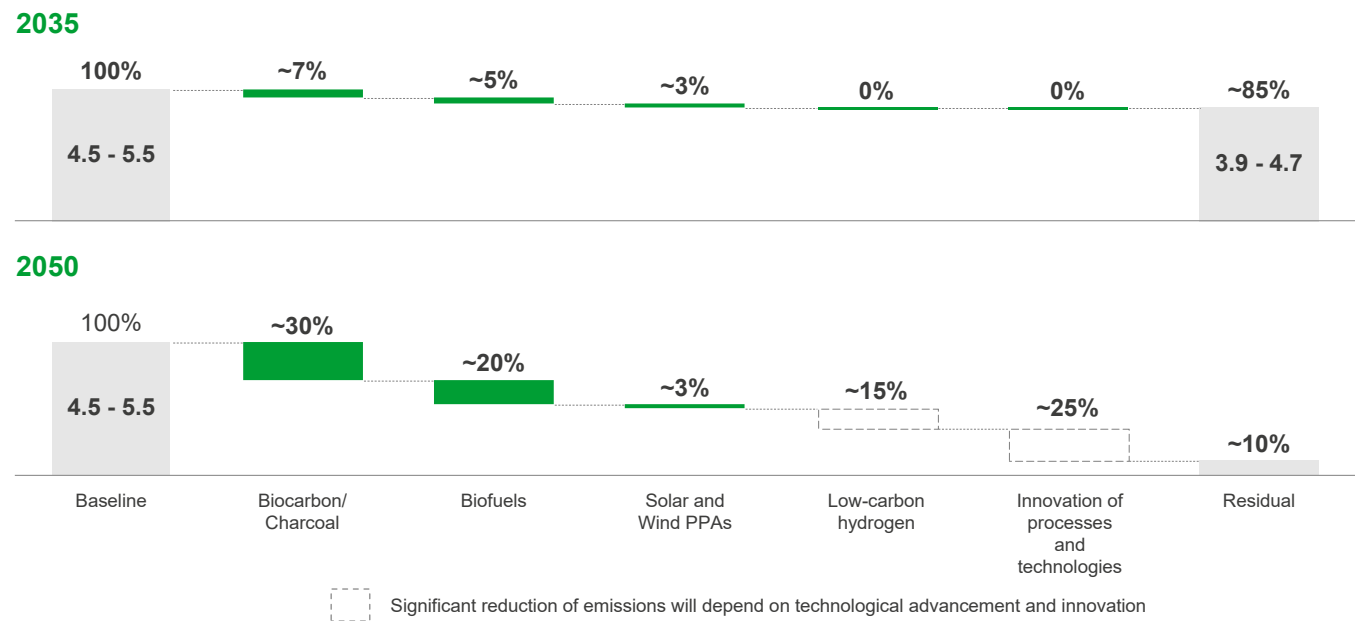


Figure 25 – Pelletizing Scope 1 and 2 reduction potential (MtCO₂e)



Sources: Sustainability reports; GHG Protocol; Interviews with Coalition members

Figure 26 – Levers of the iron ore chain – Pelletizing

Levers	Current feasibility analysis	References
1 Use biocarbon or charcoal during pelletizing to partially replace coal in the combustion process	 Viable pilot; depends on stable biomass and thermal adjustments in the furnace; challenges associated with lower density, combustion risk and more complex logistics	Pelletizer of Vale in Vargem Grande (MG) Samarco pelletizers
2 Use biofuels as bio-oil or biomethane as a substitute for natural gas in pelletizing furnaces	 Validated technology in industrial testing; continuous availability and ability to scale limited production and distribution	Partnership between Samarco and Aperam BioEnergia LKAB's HYBRIT pellet plant in Malmberget, Sweden
3 Implement solar and wind PPAs to eliminate scope 2 and foster electromobility	 Highly feasible in Brazil due to maturity of PPAs contracts – can be deployed quickly	Vale: Sol do Cerrado solar complex supplying ~16% of the company's electricity in the country with a reduction of ~134 kt CO ₂ per year CBA: installed capacity to generate 100% renewable electricity through 21 hydroelectric power plants and 2 wind farms
4 Use low-carbon hydrogen as a heat source in pelletizing furnaces, partially or totally replacing natural gas	 Emerging technology in pilot phase; requires burner retrofit, reliable H ₂ supply and safety infrastructure	LKAB's HYBRIT project (Sweden) Ferrexpo Electrolysis Pilot (Ukraine) Samarco's partnership with Eletrobrás and SMS Group to develop green H ₂ to replace NG in furnaces
5 Use CO₂ capture in furnaces or boilers to eliminate emissions via injection into a geological reservoir	 Mature technology in the steel industry; requires proximity to wells and CO ₂ transport; high CAPEX and OPEX	Vale and RTI International study – eCO ₂ Sol™ solvent in Tubarão LKAB Pelletizing Plants Study: Kiruna & Malmberget (Sweden) Protocol of intentions of Petrobras, Findes ¹ and the Government of Espírito Santo for studies of CCUS and production of low-carbon hydrogen

Note: PPAs (Power Purchase Agreements) are long-term energy purchase and sale agreements.

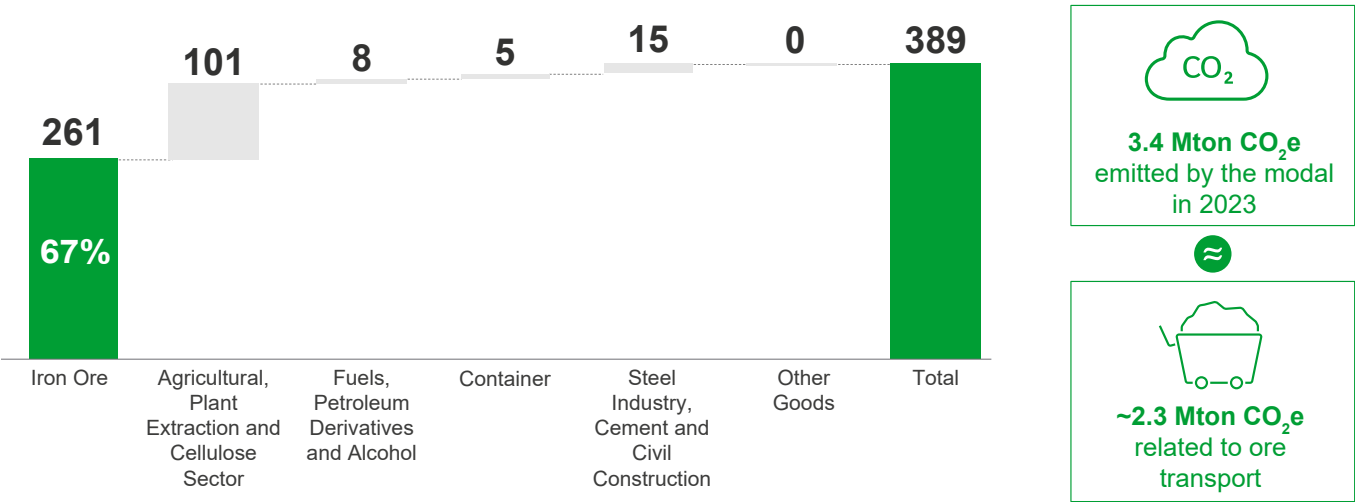
1. Federation of Industries of Espírito Santo

3.4 Reduction of logistical emissions linked to rail transport

Rail transport accounts for about 3.4 MtCO₂e per year in Brazil, of which approximately 70% is linked to iron ore. Expanding mineral production could significantly increase emissions by 2050.

The **mitigation levers**, discussed in detail in the **Transport Coalition**, include efficiency gains, use of biofuels and partial electrification of the lines. The reduction potential ranges from **50% to 80% by 2050 depending on the scenario considered**, leading to residual emissions between **0.6 and 1.4 MtCO₂e**.

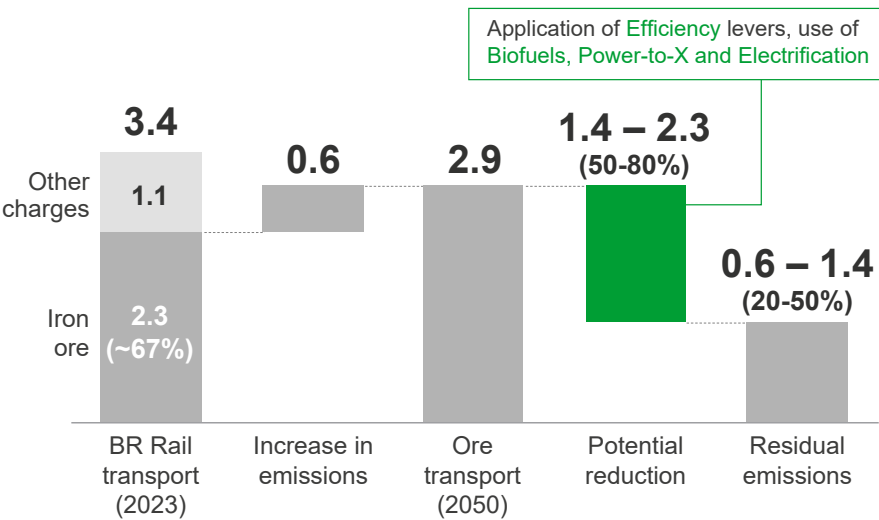
Figure 27 – Rail Transport by Commodity (Billions of TKM1)



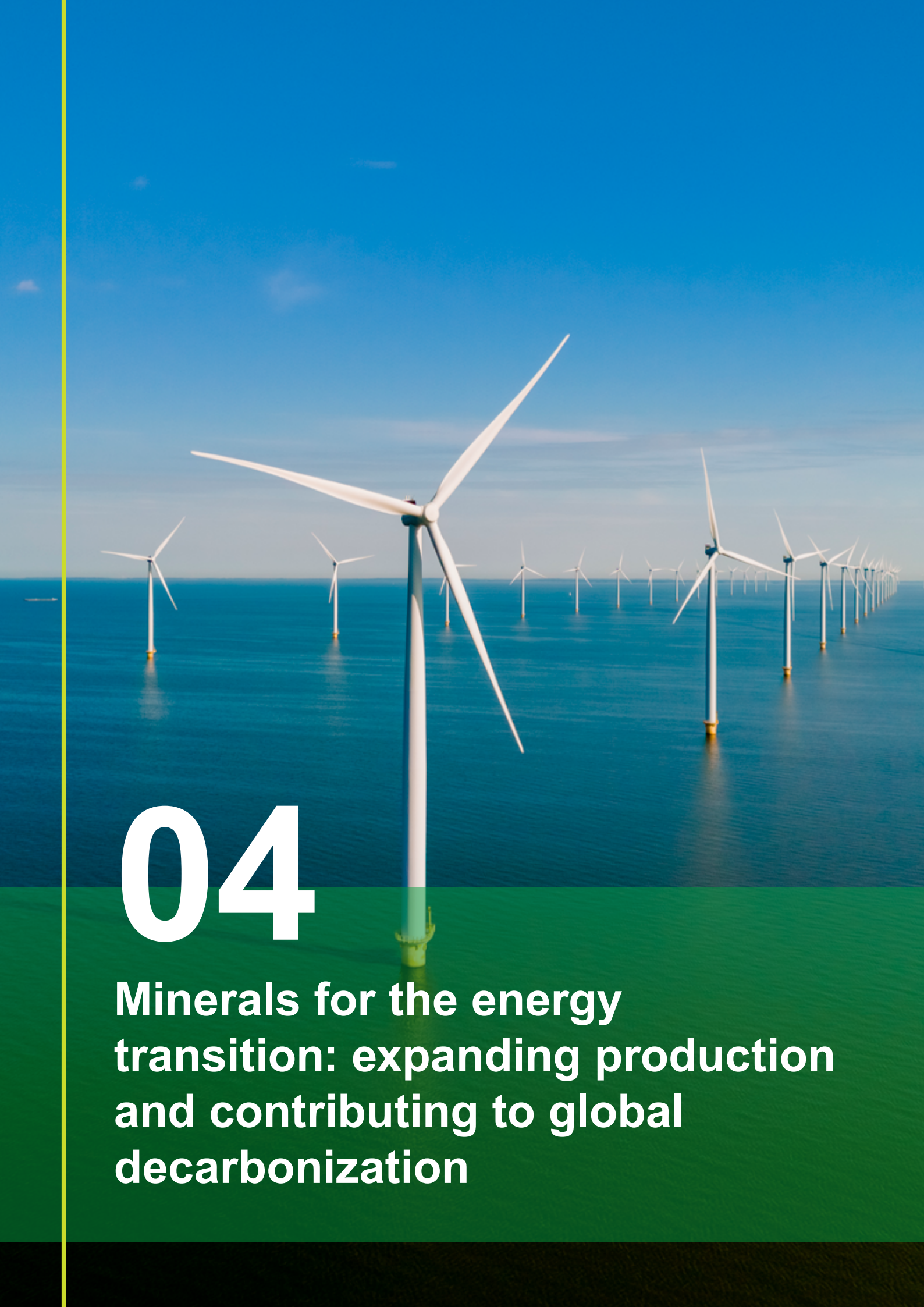
1. Ton-Kilometer 2. Iron ore emissions estimated based on its share in TKM (67%) applied to total modal emissions in 2023, an approximation that may overestimate iron ore emissions in relation to less dense cargoes Source: National Association of Rail Transporters (ANTF); SEEG

This reduction faces a key hurdle: the viability of electrification across extended, high-throughput routes, which hinges on significant infrastructure investments and a carbon pricing framework that ensures competitiveness. Even so, there is a relevant contribution to be made, especially in the medium term, through the replacement of diesel with biofuels.

Figure 28 – Emissions from ore rail transport (Mt CO₂)



Source: SEEG; ANTF; [Transport Coalition](#)

A large-scale photograph of an offshore wind farm. Numerous white wind turbines with three blades each are spaced out across a deep blue ocean under a clear sky. The perspective is from a low angle, looking across the water towards the horizon where the turbines recede into the distance. A solid green horizontal band is at the bottom of the image, and a thin yellow vertical line runs down the left edge.

04

Minerals for the energy transition: expanding production and contributing to global decarbonization

Brazil has a tremendous potential to expand its mineral production and, as such, contribute significantly to the global energy transition. The growing demand for **low-carbon technologies**—such as electric vehicles, storage systems and renewable energy sources—depends on several mineral inputs, **many of which are available in abundance throughout the country**. In this scenario, Brazilian production can help rank the country as **one of the top global suppliers of minerals needed for the energy transition**.

The Coalition's work involved **objectively quantifying** the role of the Brazilian mineral sector within this process, based on three main steps:

- **Selection of minerals for quantification:** establishing a set of minerals with reserves in Brazil and indispensable for energy transition technologies, considering their relevance for applications such as batteries, renewable energies and electrical grids.
- **Projection of Brazilian production:** expansion estimates on how much the production of minerals in Brazil is expected to grow by 2050, in line with global growth trends.
- **Emission impact assessment:** calculation of the potential effect on greenhouse gas emissions in Brazil and worldwide, considering the contribution of these minerals to the replacement of polluting sources of energy generation.

The Brazilian potential outlined below—which involves **the accelerated growth of mineral production** and associated value chains—**will depend on favorable systemic conditions, including a regulatory environment** that simultaneously promotes rigorous

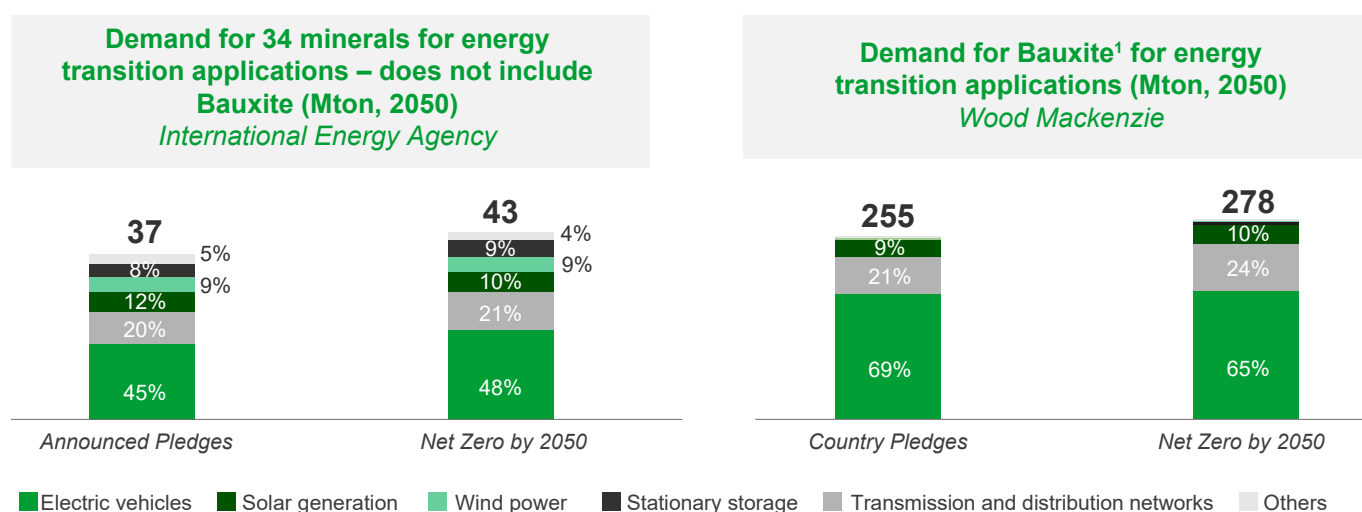
sustainability standards for licensing and operation and allows for the agile expansion of productive areas to meet growing demand and develop the Brazilian mineral sector.

4.1 Expansion of mineral production for the energy transition

4.1.1 Selection of ores for quantification

A number of countries and international organizations have created their own lists of minerals classified as **"critical"** or **"strategic"**, based on criteria such as **dependence on imports, concentration of global supply and relevance to high technology or defense sectors, updating them periodically, according to the national and international context**. In the United States, for example, the U.S. Geological Survey (USGS) regularly reviews its list of critical minerals as industry priorities and supply risks evolve. Similarly, the European Union publishes its list of Critical Raw Materials every three years, adjusting the ranking according to demand trends, new technological applications and vulnerabilities in the global supply chain. These classifications often provide guidance on public policies, research incentives, supplier diversification strategies and national security mechanisms

Figure 29 – Potential scenarios involving the demand for minerals for energy transition applications

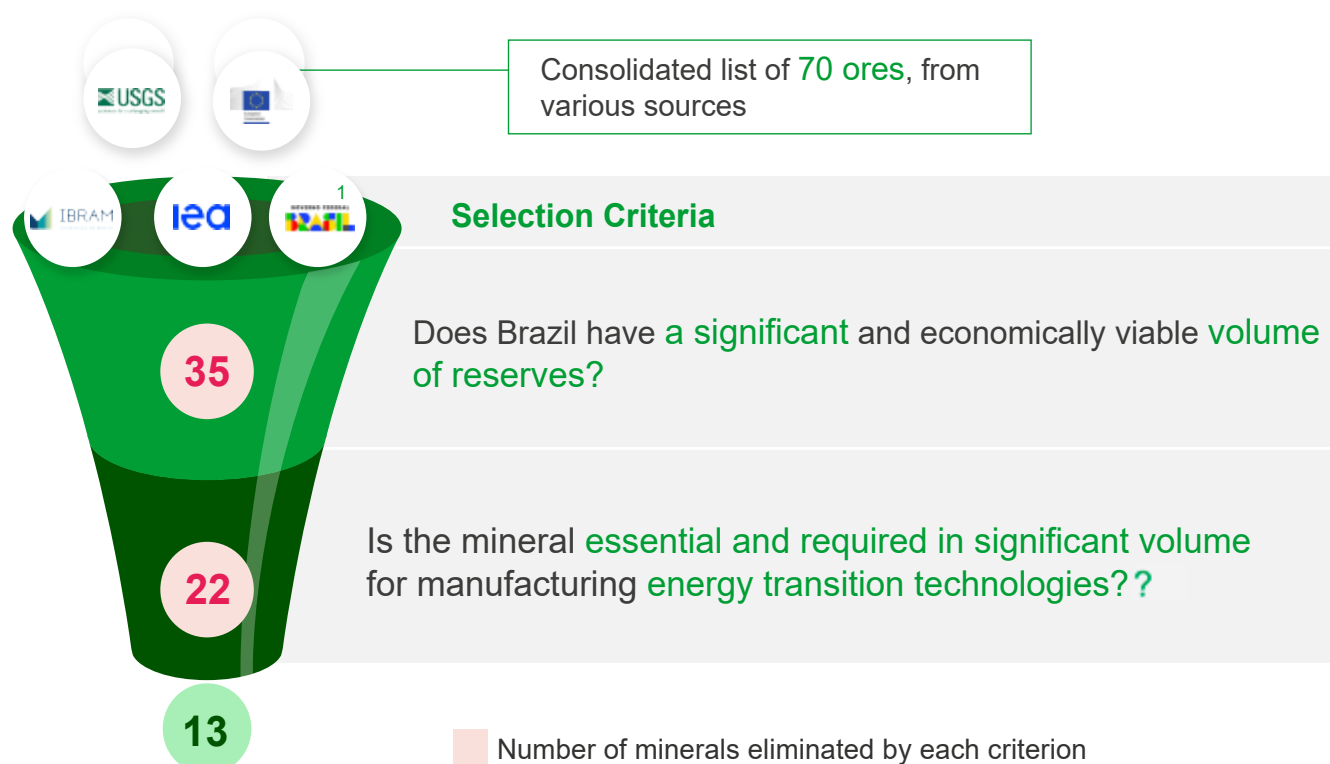


1. Assuming 5 tons of bauxite needed to produce 1 ton of aluminum Note: Stated Policies Scenario was not included in the study, as it does not consider climate commitments already made by countries and companies. Sources: IEA Global Critical Minerals Outlook Data Explorer (2024), Wood Mackenzie - Aluminium at a crossroads: synchronising supply growth with decarbonisation (2025)

This study, however, is not intended to define which minerals should be considered as critical or strategic for Brazil or the world, since this discussion involves multiple factors of public policy and economic security that are outside the scope. These efforts are focused on **identifying minerals in which Brazil has the potential for significant production and that are expected to see accelerated demand growth due to the energy transition.**

Thus, **five main applications of the energy transition were considered: electric vehicles, transmission and distribution networks, wind generation, solar generation and stationary storage**—which, according to the International Energy Agency (IEA), are expected to concentrate more than 90% of global demand for minerals by 2050. While not included in the IEA projections, Bauxite was also considered, given the key role of aluminum in several of these applications (in particular, for electric vehicle chassis, power transmission and distribution infrastructure and solar panel frames).

Figure 30 – Selection funnel of minerals for quantification



The selection of minerals considered to quantify the impact on emissions came from a **consolidated list of 70 minerals**, created from various sources, including both national sources like (IBRAM and the Federal Government) and international (USGS, IEA and the European Union). On this basis, **two selection criteria** were applied. The first was to assess whether Brazil has **significant and economically viable reserves** for production at scale (according to the USGS and Studies for PNM 2050). The second sought to identify whether the mineral is **essential and significant in terms of volume for manufacturing technologies related to energy transition**—in line with the reasoning previously developed, which highlighted five

main applications (electric vehicles, transmission and distribution networks, solar generation, wind generation and stationary storage).

As a result of the application of these filters, 35 minerals were excluded for not meeting the first criterion, and another 22 for not meeting the second, resulting in a set of **13 minerals selected for analysis: bauxite, manganese, copper, zinc, silicon, niobium, nickel, graphite, vanadium, lithium, tantalum, rare earths and cobalt.**

Figure 31 – Projection of global demand for minerals for transition applications¹

Ore	Brazilian production 2023	Total production and for energy transition (kt)	Brazilian share of global production	Main applications in energy transition	CAGR 2024-50 total demand ²	CAGR 2024-50 demand for energy transition ²	Demand multiplier for energy transition ² 2050 vs. 2024
Bauxite	34.530	438.000 123.000	7%	    	1%	3%	2.2x
Manganese	580	19.600 186	3%	  	1%	14%	29x
Copper³	358	22.600 7.737	1%	    	2%	4%	2.5x
Zinc³	210	12.100 764	2%	 	1%	4%	2.4x
Silicon	196	4.280 1.499	5%	  	2%	2%	1.8x
Niobium	102	110 0.3	93%		1%	7%	5x
Nickel	83	3.750 562	2%	  	3%	8%	8x
Graphite	66	1.530 1.505	4%	 	5%	7%	6x
Vanadium	5	104 -	5%		9%	N/A ⁴	N/A ⁴
Lithium	5	204 128	3%	 	9%	10%	13x
Tantalum	0.1	2 0.1	7%		3%	2%	1.7x
Rare Earths⁵	0.04	75 19	<1%	 	3%	6%	4x
Cobalt⁶	0.03	238 71	<1%	 	3%	6%	4x

 Electric vehicles  Wind power  Solar generation  Stationary storage  Electrical grid

1. Electric vehicles, wind generation, solar generation, stationary storage and electrical grid 2. According to the IEA or Wood Mackenzie (in the case of bauxite), in the Net Zero by 2050 scenario 3. 2022 data from studies for PNM 2050 (not released by the USGS) 4. Current demand for energy transition is zero 5. Current production released by Mineração Serra Verde 6. Current production released by Atlantic Nickel. Sources: IEA, IBRAM, United States Geological Survey (USGS), European Commission, Wood Mackenzie, Studies for PNM 2050, Brazilian Government

Figure 31 shows the thirteen minerals selected, with information on Brazilian production, the relevance of the country's production in global demand and its main applications in energy transition technologies. The compound annual growth rates (CAGR) of demand up to 2050 are also indicated. It is noted that **for the selected minerals, growth is driven by the energy transition**, which is evident in the comparison of total growth rates and associated with the energy transition.

Beyond the minerals selected, **iron ore is prominently important for energy transition solutions**. Steel is an essential input in significant volumes for wind turbines, solar plants and transmission networks. Given its volume, relevance to multiple other applications, and the prior discussion on value chain decarbonization, it was excluded from the quantification.

Figure 32 – Projections of Brazilian production of minerals for the transition

Ore	Annual demand growth (CAGR) 2023-2050							Brazilian production 2050 (kt)			
	Brazilian global production and share 2023 (kt)		Global in the APS scenario	Global in the NZS scenario	Energy transition in the NZS scenario	PNM	Adopted range	Brazilian global production and share 2050 (kt)		Percentage and produc- tion (kt) for the energy transition¹	
Bauxite^{2,3}	34,530	8%	0.7%	0.9%	2.5%	1.6%	0.7% – 2.5%	41,600 – 69,900	9-15%	58%	24,280 – 40,820
Manganese	580	3%	0.8%	0.9%	14%	4.0%	0.8% – 4.0% ⁴	714 – 1,672	3-7%	22%	157 – 368
Copper³	358	1%	1.5%	1.7%	4%	4.4%	1.5% – 4.4%	545 – 1,195	1-3%	48%	256 – 499
Zinc³	210	2%	1.1%	1.1%	3%	5.0%	1.1% – 5.0%	284 – 820	2-5%	11%	33 – 94
Silicon	196	5%	2.1%	2.2%	2.4%	N/A ⁵	2.1% – 2.4%	343 – 369	~5%	37%	127 – 137
Niobium	102	93%	1.3%	1.3%	7%	3.7%	1.3% ⁶	~144	~94%	1%	~1.5
Nickel	83	2%	3.0%	3.2%	8.3%	5%	3.0% – 8.3%	183 – 717	2-9%	59%	108 – 424
Graphite	66	4%	3.5%	5.0%	7%	5%	3.5% – 7.0%	166 – 389	3-8%	49%	121 – 192
Vanadium	5	5%	8.5%	9.1%	N/A ⁷	2.5%	2.5% – 9.1%	11 – 57	1-6%	83%	9 – 48
Lithium	5	3%	8.1%	8.8%	10%	7.5%	4.9% – 10.4%	19 – 76	1-4%	92%	19 – 70
Tantalum	0.1	7%	3.0%	3.0%	2.1%	N/A ⁸	2.1% – 3.0%	0.24 – 0.34	6-8%	4%	~0.01
Rare Earths	0.04	<1%	-	-	1.2% ⁹	0% ¹⁰	N/A ¹¹	1.4 – 1.8	~1%	36%	0.6 – 0.7
Cobalt	0.03	<1%	-	-	0.4% ¹²	2.4% ¹³	N/A ¹⁴	5.0 – 9.5	1-2%	58%	2.9 – 5.5
Total	36 Mt	7%						44 ~ 75 Mt	8-13%		25 ~ 43 Mt

Note: APS = Announced Pledges Scenario; NZS = Net Zero by 2050 Scenario 1. Based on data estimated for 2050 by the IEA for production destined for energy transition 2. Considering only demand for primary aluminum 3. Current production according to the Brazilian Aluminum Association (ABAL) 4. The percentage allocated to the transition today is very small (1%), therefore, using the CAGR of the transition leads to an inconsistent result (Brazilian production equaling 80% of world production by 2050) 5. PNM 2050 plan does not include any predictions for silicon production 6. The percentage allocated to the transition today is very small (0.3%), therefore, using the transition CAGR leads to an inconsistent result (Brazilian production higher than the world production by 2050, as well as the use of the PNM CAGR) 7. Current demand for energy transition is zero 8. PNM starts production of 380 kton of tantalum ore in 2022 (equivalent to ~100 kton of metallic tantalum, depending on the Ta2O5 content), far from the scale disclosed by the USGS and current players 9. CAGR 2030-2050 (based on the projections available for projects through 2030) 10. According to PNM, the value of annual rare earth production is constant from 2025 to 2050 (12 kt) 11. The starting point was calculated based on forecasts of anticipated projects, applying estimated CAGR from 2030 12. The starting point was calculated based on forecasts of anticipated projects, applying estimated CAGRs from 2035 13. CAGR 2030-2050 (start of production in 2030) 14. CAGR 2035-2050 (based on the projections available for projects through 2035) Sources: USGS, IEA, Wood Mackenzie, Studies for PNM 2050

4.1.2 Growth projections of Brazilian production

The development of Brazilian mineral production up until 2050 will depend on multiple factors, involving both national and international conditions. These factors include the availability of investments, the degree of certainty regarding future demand, the dynamics of global commodity markets and the development of new technologies, which might even introduce unforeseen substitutes for certain input. This set of variables generates relevant uncertainties about the pace of expanded production. As such, **to harmonize differing views and capture the range of possible futures, the study adopted broad growth intervals** in projecting trends for the 13 selected minerals.

The estimates of growth in Brazilian production were defined based on **global demand projections** published by the International Energy Agency (IEA) and Wood Mackenzie, complemented by the **Studies' projections for PNM 2050**. In addition, for specific minerals, the estimates were adjusted considering **capacity expansions that had been previously announced and relevant projects published** by the main players in the sector.

The forecast of growth for Brazilian production up to 2050 was formulated based on **annual growth rate intervals** that combine three main references: the global projections of total demand, the specific projections for the energy transition and the national projections from the PNM 2050. The most conservative scenario (lower range) adopts, for each mineral, the lowest CAGR observed, while the most optimistic

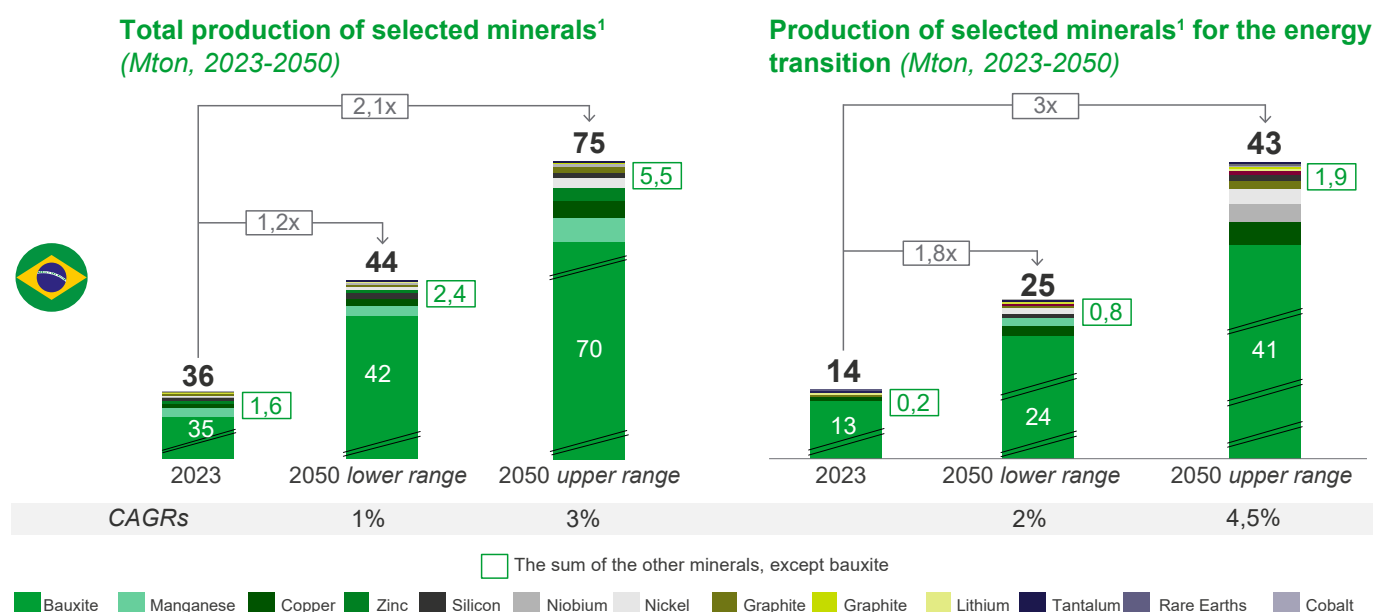
scenario (upper range) uses the highest. Thus, **the interval seeks to capture the breadth of available views and reflect the uncertainties associated with the future of demand and supply**.

Overall, **Brazil tends to sustain its relative share of the global market in conservative scenarios and boost this share in optimistic scenarios**, as illustrated by the participation indicators next to the estimated production values.

As a result, the Brazilian production of selected minerals can evolve from the current 36 Mt (1.6 Mt, excluding bauxite) to a range **between 44 and 75 Mt** in 2050 (2.4 and 5.5 Mt, excluding bauxite). The percentage of production intended specifically for the energy transition follows the estimates of the International Energy Agency (IEA). As such, roughly **25 to 43 Mt would be allocated to applications associated with the energy transition** (0.8 to 1.9 Mt, excluding bauxite), reinforcing Brazil's strategic role as a global supplier of critical inputs for low-carbon technologies.

In the consolidated view of the different projections, it can be seen that the total production of the selected minerals should reach **between 1.2 and 2.1 times the current levels** by 2050. The growth is more significant in the case of production for the **energy transition**, ranging from **1.8 to 3.0 times** in the same period. The findings indicate that the share linked to the energy transition is poised to grow in relative significance, becoming a major catalyst for the expansion of Brazil's mineral output.

Figure 33 – Brazilian production of Minerals for Transition – 2023 and 2050



1. 13 minerals selected for study 2. Based on data estimated for 2050 by the IEA for production destined for energy transition. Sources: USGS, IEA

BNDES, FINEP and Vale: more than R\$45 billion mobilized for strategic minerals in Brazil

The Brazilian Development Bank (BNDES) has been actively focusing its efforts on **strengthening the supply chain for minerals deemed strategic for energy transition, decarbonization, and the sustainable production of food.**

The Bank, in collaboration with the Brazilian Innovation Agency (FINEP), approved **56 business plans** in June 2025 under the public call for the transformation of strategic minerals, dedicating a total of R\$45.8 billion to the subsequent implementation phase, known as the **Joint Support Plan (PSC)**. The projects encompass a variety of minerals that are important to clean technologies, with an emphasis on **rare earths (10 projects), lithium (8), graphite (6), copper (4) and silicon (4)**. The approved plans will move on to the structuring phase of the PSC. In this phase, financial instruments such as lines of credit, grants, and non-repayable resources will be identified to make the projects feasible.

Also in 2025, the bank partnered with Vale to launch the FIP Minerais Estratégicos (Strategic Minerals Private Equity Fund), aiming to mobilize more than R\$1 billion. The funds will be allocated to junior and medium-sized companies working in mineral research, development and implementation of new mines, with the expectation of supporting between 15 and 20 projects in Brazil.

Initiatives such as these are viewed as impactful actions taken by the sector, in cooperation with the government. These initiatives seek to ensure the supply of strategic minerals in a competitive and sustainable manner, promote innovation, enhance supply security, and strengthen Brazil's position in global value chains related to energy transition and low-carbon agriculture. These mechanisms, along with other enablers, can help the sector respond to growing demand and achieve the ambitious expectations of doubling its production by 2050.

4.2 Emissions impact

4.2.1 Global emissions impact in 2050

The estimate of Brazilian mining's contribution to the global energy transition considered the cumulative production projections between 2025 and 2050 for energy transition applications, discussed in the previous section, and its global share in key applications—specifically, electric vehicles, solar panels, and wind turbines, as well as other essential structures such as transmission grids, stationary storage systems, and vehicle chassis. The Coalition then made an assessment of the impact that these applications would have in terms of mitigating emissions, in their stage of use, would prevent by replacing emitting technologies. It should be pointed out that this approach focused on the use stage of energy transition applications has limitations and could be complemented by the analysis of emissions throughout the value chain, which was not covered in this study.

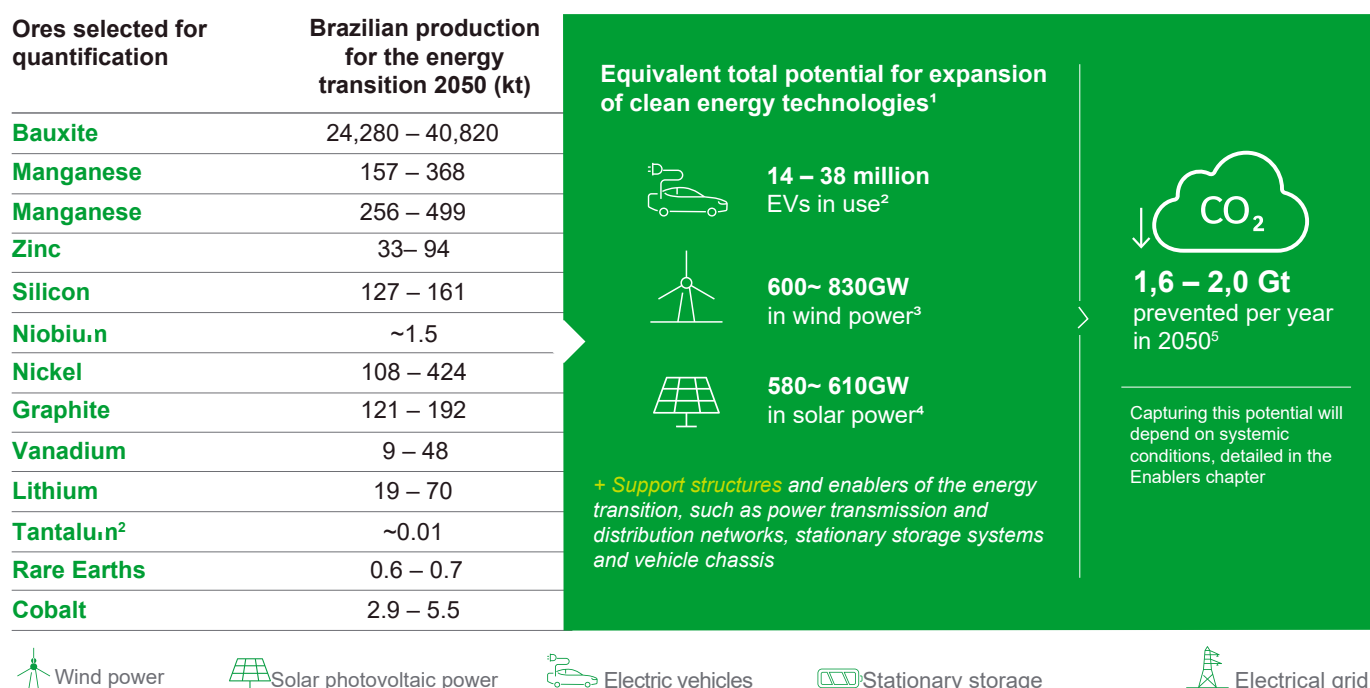
The analysis indicates that, with the expansion of mineral production for the transition, Brazil is expected to be able to supply enough minerals to enable **the production of 14 to 38 million electric vehicles,**

about 600 to 830 GW of installed wind power generation capacity and approximately **580 to 610 GW of installed solar power generation capacity**, in addition to other essential infrastructure for the energy transition.

These technologies, through the replacement of polluting sources—that is, the elimination of gasoline-powered vehicles and electricity generated by fossil fuels—can enable the mitigation of greenhouse gases estimated at **between 1.6 and 2.0 billion tons of CO₂e in 2050 globally**—a quantity comparable to the total Brazilian gross emissions in 2023, of approximately 2.3 billion tons of CO₂e.

Realizing this potential **depends directly on strengthening critical enablers**—technology and R&D, infrastructure, financing, green premium and value chain, in addition to the regulatory-economic scenario. These elements are **absolutely essential to ensuring that Brazilian mineral production is effectively converted into inputs for the energy transition.**

Figure 34 – Brazilian production can enable a reduction of 1.6-2.0 GtCO₂e



1. The analysis assumes that Brazilian mineral inputs are allocated to technology manufacturing in line with Brazil's production share of each key mineral: bauxite for wind power, silicon for solar technologies, and nickel for EV batteries across vehicle classes (light and heavy). 2. From 2% to 6% (share of nickel demand) of a total fleet of 2 billion electric vehicles in 2050 (estimated by the IEA in the Net Zero scenario). 3. From 9% to 12% (share of bauxite demand) of the expansion of 7 TW of installed capacity up to 2050 4. Approximately 5% (share of silicon demand) of the expansion of 12.7 TW of installed capacity up to 2050 5. Considering direct replacement of fossil sources: 1.8 tons CO₂e per year for each ICEV replaced; 480 tCO₂e per GWh of energy generated (average of fossil sources weighted by installed capacity)

Sources: IEA, Climate Trace, USGS, Studies for PNM 2050

4.2.2 Impact on Brazilian emissions in 2035 and 2050

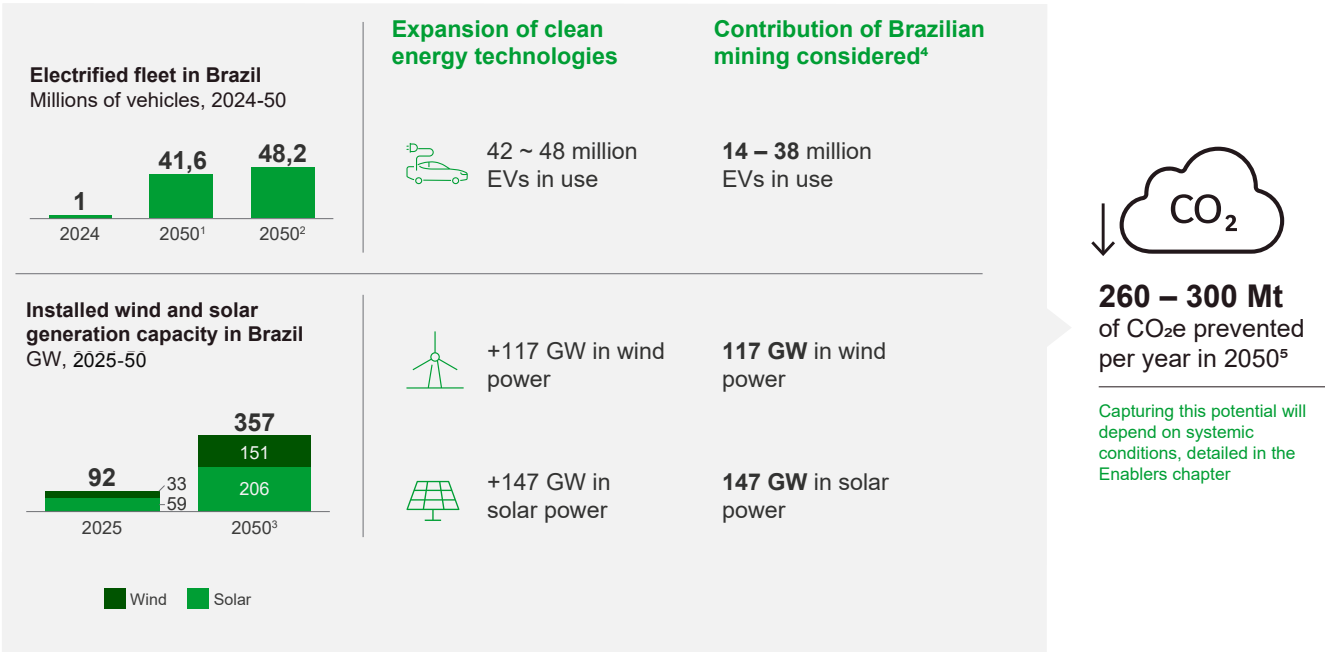
As Brazilian mineral inputs will feed global production chains, mining is expected to indirectly contribute to the decarbonization of the Brazilian economy through the same applications, which will replace fossil emission technologies in Brazilian territory.

Comparing the estimated global potential with the projected demand for these applications in Brazil, **the Brazilian mineral contribution could prevent between 260 and 300 million tons of CO₂e per year in 2050**. This figure is comparable to the 2023 emissions of the states of São Paulo and Minas Gerais combined.

Reproducing the analysis for 2035, there is a potential for reduction from technologies produced with Brazilian minerals of **60 to 75 million tons of CO₂e per year in 2035**, a figure comparable to the 2023 emissions of the state of Rio de Janeiro.

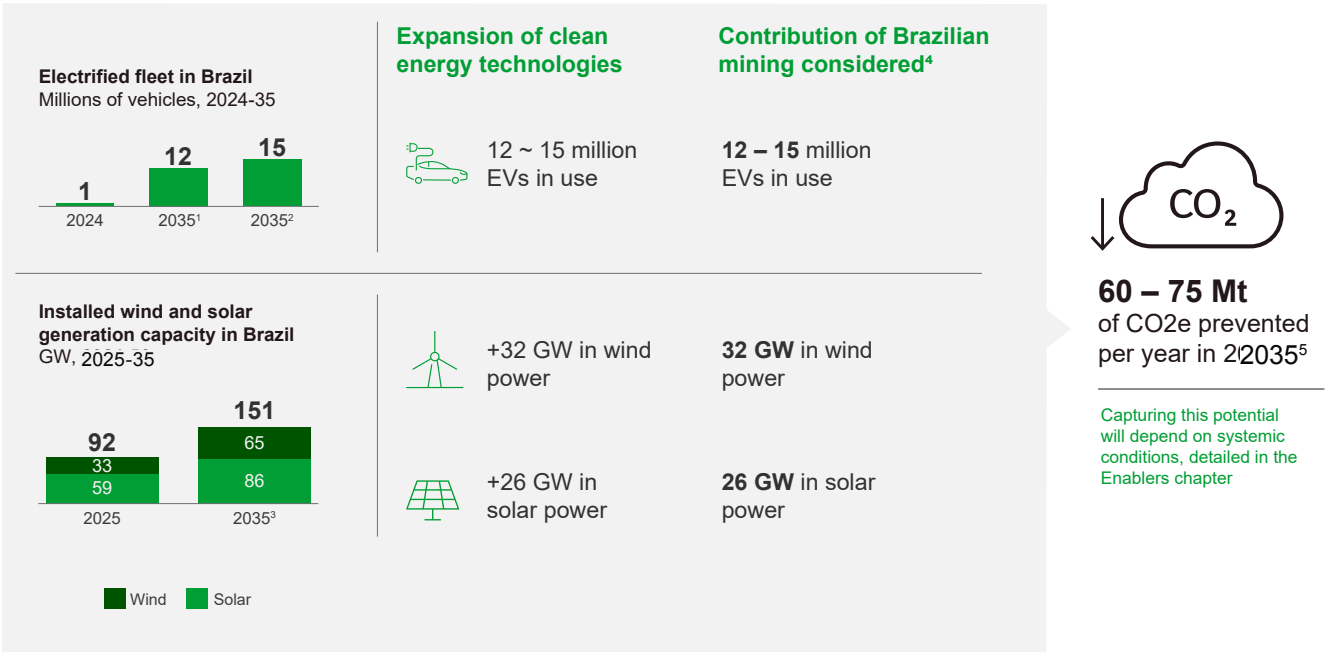
The forecast for the indirect impact on Brazilian emissions considered the anticipated growth in local energy transition technologies, such as electric vehicles, solar panels, and wind turbines. In the case of electricity generation, the scenarios defined by the Energy Coalition were used. For electric vehicles, the figures defined by the Transport Coalition were used, which predicted the progressive electrification of the vehicle fleet in Brazil under various scenarios.

Figure 35 – In Brazil, contribution may reach 260-300 MtCO₂e in 2050



1. Scenario of a gradual increase in the adoption of new engine technologies 2. Scenario of a rapid convergence towards fleet electrification, with BEVs assuming dominance in sales 3. Brazilian electricity matrix forecast prepared by the Energy Coalition 4. Based on the projected expansion of the Brazilian energy matrix, limited to the production potential of mining for transition 5. Considering direct replacement of fossil sources: 1.8 tCO₂e per year for each ICEV (Internal Combustion Engine Vehicle) replaced; 480 tCO₂e per GWh of energy generated (average of fossil sources weighted by installed capacity).
Sources: Transport Coalition (Road Modal), Energy Coalition

Figure 36 – Transition fostered by mining activities could reduce Brazilian emissions by 60-75 MtCO₂e by 2035



1. Scenario of a gradual increase in the adoption of new engine technologies 2. Scenario of a rapid convergence towards fleet electrification, with BEVs assuming dominance in sales 3. Brazilian electricity matrix forecast prepared by the Energy Coalition 4. Based on the projected expansion of the Brazilian energy matrix, limited to the production potential of mining for transition 5. Considering direct replacement of fossil sources: 1.8 tCO₂e per year for each ICEV (Internal Combustion Engine Vehicle) replaced; 480 tCO₂e per GWh of energy generated (average of fossil sources weighted by installed capacity).
Sources: Transport Coalition (Road Modal), Energy Coalition



05

**Enablers for the decarbonization
of the mineral sector and
expansion of minerals for the
energy transition**

Materializing the mining contributions discussed requires systemic enablers. These are conditions that must be collaboratively developed and improved alongside various stakeholders. This chapter will focus on explaining enablers, including a detailed presentation of their importance in Brazil's path towards decarbonization and examples of concrete initiatives that can contribute to strengthen these conditions.

Enablers are organized into five groups: advancements in **technology and R&D**, ensuring technical maturity and the viability of low-carbon solutions; logistics, energy, and storage **infrastructure** with capacity to support current operations and new projects; green **financing** mechanisms and sustainable taxonomies capable of reducing risks and expanding access to capital at scale; the consolidation of a value chain ecosystem, based on green premiums and traceability, that ensures predictable demand for low-carbon

minerals and aligns incentives throughout the production chain; and, finally, a stable **regulatory and economic environment**, with aligned incentives and carbon pricing that guide investments in the sector.

Among the regulatory and economic enablers analyzed, **carbon pricing** stands out as a critical enabler of the path towards decarbonization. By assigning an economic value to emissions, a market signal is created. This signal **helps guide investments and increases the competitiveness of low-carbon solutions** in the mineral sector. This study references projections from the International Energy Agency (IEA) under the Announced Pledges Scenario (APS) and Net Zero by 2050 (NZE). These scenarios feature **pricing levels strong enough to decisively stimulate investment in sustainable practices and technologies.**

Figure 37 – Mining contributions will depend on a context favorable to decarbonization – enabling scenario by 2050:



1. Price ranges defined by the IEA Announced Pledges and Net Zero by 2050 for the category "Emerging markets and developing economies with net zero emissions pledges" - Global Energy and Climate Model Documentation 2024 (IEA)

5.1 Technology and R&D

Enablers related to Technology and R&D integrate a set of fundamental structural conditions with a focus on innovation, efficiency and competitiveness in low carbon. This entails establishing structural incentives to foster the **development of applied solutions**, including heavy-fleet electrification, the use of advanced biodiesel, low-carbon hydrogen, and enhanced ore processing and transport. These can significantly reduce the sector's carbon footprint.

Also, investing in **high-resolution geological mapping** that is publicly accessible is vital. It's a strategic asset that guides investment decisions, helps reduce exploratory uncertainties and strengthens the knowledge base of the mineral sector. In Brazil, programs such as PlanGeo of the Geological Survey of Brazil—which is used to systematically map areas with mineral potential—exemplify this need.

Finally, the R&D environment should also include the development of **technologies and expertise applied to the beneficiation of minerals**—especially those related to the energy transition, whose demand grows rapidly and whose added value increases significantly at this stage of the chain. Investing in this field can encourage the emergence of a more sophisticated domestic industry and reduce the current concentration of global value chains, currently dominated by a few countries, such as China.

5.1.1 Hydrogen and cost reduction

In this study, levers for the decarbonization of the mineral sector were proposed, which include the adoption of hydrogen as an energy input. In transportation and in industrial processes that are difficult to reduce, hydrogen appears as a strategic alternative to replace high-carbon intensity fuels. Its use may represent a structural transformation, paving the way for low- or even zero-carbon solutions in chains historically dependent on coal and fuel oil.

Despite its potential, **hydrogen diffusion faces relevant barriers**. The most significant is **production costs**, still extremely high compared to conventional fossil fuels, making it unfeasible to widely adopt the technology in the mining sector. Moreover, the technological development of electrolyzers, industrial-scale production, and the availability of dependable, high-volume renewable energy are determining factors for their competitiveness. Another critical point is the **necessary logistics infrastructure**—from secure storage to distribution—which is still at an early stage in virtually all global markets.

Within this context, **research and development** are becoming more strategically important. Technological advances have the potential to reduce costs, increase the efficiency of electrolysis processes and develop alternative routes, such as the use of green ammonia or methanol as energy vectors. Likewise, **coordination between public policies, incentive instruments and private investments will be decisive** to enable hydrogen projects on an industrial scale. For Brazil, which has abundant renewable resources, the challenge is to transform this natural advantage into technological and competitive leadership, ensuring that hydrogen becomes a realistic and economically viable vector of the decarbonization of the mineral sector.

Figure 38 – Recent Examples – Technology and R&D Enablers

Selected examples: R&D programs applied to decarbonization		
✓	EIT Raw Materials – consortium with public funding and private co-investment (EU – European Union) <i>EIT has already mobilized +€3.6 billion for applied R&D projects, bringing together companies, universities, and technology centers in innovative initiatives such as ReLieVe—a pilot project for lithium battery recycling developed in partnership with BASF, Eramet, and Suez</i>	
✓	Miner – publicly funded program (Department of Energy – USA) <i>Focusing on innovative and high-tech-risk R&D projects, the program has already earmarked US\$39 million for university- and startup-led research projects, such as the University of Texas, focused on electrochemical nickel and lithium extraction</i>	
Selected examples: development of technologies for decarbonization		
✓	BeVant from Be8, Biodiesel can be used 100% pure in diesel engines (Rio Grande do Sul) <i>Developed by Be8, BeVant can be used in its pure form directly in diesel engines. In 2025, it was adopted at Congonhas Airport (São Paulo) in runway vehicles and generators and is in the testing phase in Alcoa fleets in Juriti, in addition to Gerdau and Ambipar operations</i>	
✓	Genium from Seventeen66, H₂ partial injection technology to reduce diesel consumption <i>Genium's electrolysis system injects pure hydrogen on demand into diesel engines to act as an additive, reducing around 10% of fuel consumption and almost 20% of emissions. The technology is in the testing phase at Alcoa's Juriti and Poços de Caldas units</i>	

5.2 Infrastructure

Infrastructure is one of the fundamental pillars to enable the decarbonization of mining as it creates the physical and systemic conditions necessary for the adoption of new technologies and low-carbon fuels. The feasibility of alternative fuels and low-carbon technologies is directly associated with the **existence of proper logistics and electrical grids, especially in remote mining regions**. Without sufficient infrastructure, both the adoption of electrification and clean fuel solutions and the expansion of essential mineral production itself face significant cost, reliability and scale barriers.

The topic spans multiple complementary dimensions: the **production, distribution, and storage of biofuels** are essential to ensuring the supply of alternatives to diesel, such as ethanol and biodiesel, thereby enhancing the sector's competitiveness; **the expansion of the power transmission and distribution network** is a fundamental condition for enabling the electrification of heavy equipment, ensuring operational continuity, and integrating dispersed renewable sources into the national grid; finally, **mineral production outflow infrastructure** plays a decisive role in reducing logistics costs and aligning transport modes with low-carbon targets, ensuring that the projected growth in mineral output materializes in a sustainable and competitive manner.

5.2.1 Production, distribution and storage of biofuels

Brazil has a consolidated biofuel production base, most notably ethanol and biodiesel, which together exceeded 40 billion liters in 2023. The recent performance reflects both the country's competitiveness in sugarcane ethanol and biodiesel and the ongoing investments in productive capacity. The **distribution infrastructure** is also relatively well-developed, with a network of terminals, blending centers, and multimodal transport supporting domestic supply. **Programs such as RenovaBio** have played a role in establishing firm rules and encouraging investments, helping to create greater predictability in the sector.

Still, the sector faces some major structural challenges. One of them is **to make sure that expanded production occurs in a sustainable way** without putting pressure on sensitive ecosystems or competing with areas destined for food production, a topic that remains at the center of national and international debate. Another factor is the **logistics of disposal and storage**, still subject to regional bottlenecks, especially in remote areas. These aspects can raise costs and limit competitiveness.

Added to this is **regulatory and incentive uncertainty**, which affects the predictability of investments, as well as obstacles to obtaining financial support for projects with greater technological risk or in the early stages.

5.2.2 Expansion of the electric power transmission and distribution grid to support electrification

Expanding the adoption of various decarbonization levers related to electrification depends directly on the **availability and robustness of electrical infrastructure**. Without an adequate transmission and distribution network, especially in remote locations where many mining operations take place, it becomes impractical to enable the electrification of processes, operate electrical equipment in the field or integrate dispersed renewable sources into the national system.

This is why ensuring that energy reaches these points of consumption in a safe and stable way is one of the main enablers of decarbonization in the sector. **Investments in dedicated distribution lines, substation upgrades, and improved regional grid coverage** are essential to enable the adoption of clean technologies and sustain the competitiveness of Brazilian operations throughout the energy transition.

5.2.3 Infrastructure for mineral production logistics

The projected growth of Brazilian mineral production will require a transportation infrastructure capable of keeping up with this movement. The expansion of supply can only happen competitively if there are robust, efficient logistics systems that are aligned with the goals of decarbonization.

Brazil already has a relatively favorable base, with an emphasis on the consolidated **rail network** in logistics related to iron ore, with integrated systems that connect mines in Minas Gerais and Pará to ports in Espírito Santo and Maranhão. The expansion of the network and, in particular, its modernization are central steps to reduce dependence on diesel and align the modal with low-carbon requirements. **Waterways and coastal shipping** transport systems are also interesting alternatives, especially in regions with a natural vocation for river and maritime transport, such as the Amazon and the North Corridor. Investments in port terminals, sustainable dredging, and multimodal integration can consolidate this mode as a lower-cost, lower-carbon option for certain transport flows.

At the same time, weaknesses persist that limit the competitiveness and sustainability of the sector. While **highways continue to play an important role**, they are the mode of transportation that is most intensive in terms of emissions and remain the primary solution for areas that are not served by railways or waterways. A key challenge lies in limiting its application to critical stretches, while simultaneously developing biofuel distribution networks and, over time, electrification and hydrogen-based alternatives for heavy-duty transport.

Within this array of options, **slurry pipelines represent an already established alternative** for specific value chains, such as iron ore concentrate and bauxite. Examples such as the Samarco, Minas-Rio and Paragominas-Alunorte systems show that, in certain contexts, pipelines can combine operational efficiency with lower emissions, when driven by electric pumping. It is important to point out, however, that the solution requires careful consideration, particularly with regard to water availability.

Logistics infrastructure: more than US\$10 billion to enable expansion by 2029

According to IBRAM estimates, the Brazilian mining sector is expected to make about US\$68.4 billion in investments between 2025 and 2029. Of this total, about **US\$10.9 billion (16%) will be allocated to logistics infrastructure**.

The estimate confirms the **centrality of infrastructure as an enabler for the growth and decarbonization of mining**, suggesting that the sector recognizes the importance of strengthening its logistics capacity to sustain the increase in production.

Figure 39 – Recent Examples – Infrastructure Enablers

Selected examples: logistic hubs		
✓	Pilbara – mature logistics hub <i>Pilbara integrates 3,800 km of private railways (BHP, Rio Tinto, FMG) connecting remote mines to ports such as Port Hedland and Dampier; today it exports about 800 Mt/year of iron ore and serves as a recognized example for developing a mineral hub globally</i>	
✓	Vale do Lítio (Lithium Valley) – logistics hub under development (MG) <i>Launched in 2023 by the government of Minas Gerais, the Vale do Lítio Project has attracted R\$6.3 billion in investments from companies such as Sigma Lithium and CBL, mobilizing infrastructure, innovation and qualification in 17 municipalities in Vale do Jequitinhonha</i>	
Selected examples: infrastructure for alternative fuels		
✓	Rio Tinto and HF Sinclair, 100% HVO at Kennecott mine <i>In 2024, Rio Tinto replaced all fossil diesel with HVO in the mobile fleet at the Kennecott mine in Utah, in collaboration with the producer HF Sinclair. With 2 tanks of 18,000 installed barrels on-site for continuous supply, the mining complex became one of the first in the world to operate only on renewable diesel in heavy machinery</i>	
✓	Genium from Seventeen66, H₂ partial injection technology to reduce diesel consumption <i>In 2025, Anglo American kicked off a pilot project with the petrochemical company Sasol to produce biodiesel from moringa cultivated in these rehabilitated mining areas. In a context where national production is just beginning and demand is growing, the initiative seeks to make local supply and a short and efficient supply logistics feasible</i>	
Selected examples: infrastructure for alternative fuels		
✓	Ternium and Gás Verde – Biomethane from landfill at a thermal plant (RJ) <i>Since 2019, the Ternium steel mill has been using biomethane purified from the Seropédica (Rio de Janeiro) landfill and supplied by Gás Verde as a partial replacement for natural gas in thermal processes, while maintaining a stable operation without requiring any industrial adaptation due to the consistent and reliable supply of biofuel</i>	
✓	Vallourec – Pioneer in pelletizing with 100% charcoal (MG) <i>Since 2018, the Vallourec steel mill has operated a pelletizing plant with 100% charcoal. Three key initiatives made this possible: proprietary eucalyptus forests with integrated carbonization; technological adaptations in the grate-kiln furnace (milling, injection, thermal control); and institutional and technical support from the Sustainable Steel Project (UNDP/MMA)</i>	
✓	Vale, Petrobras, Oldendorff Carriers and Port of Singapore – Ship with B24 <i>Vale conducted its first transoceanic voyage powered by B24 biofuel in 2023, enabled by a collaboration with Petrobras (biofuel provider), Oldendorff Carriers (compatible vessel operator), and the Port of Singapore, one of the three largest global maritime hubs with bunkering infrastructure for multiple renewable fuels</i>	

5.3 Funding

Given the capital-intensive nature of mining projects—combined with long payback periods and inherent risks during exploration and feasibility—it is crucial to employ **funding structures tailored to the sector's unique needs**. Financing projects that do not have an established history of operations or verifiable reserves of resources presents a high-risk scenario for conventional investors, which often results in a high cost of capital or even difficulty in accessing credit.

Public financing can play an important role in enabling mineral projects intended to support energy transition, especially by reducing barriers to accessing credit. Dedicated financing lines or contributions via development banks offer long-term resources under conditions more appropriate to the profile of the sector. These instruments can be deployed either directly or through **blended finance structures**, in which public capital serves as an anchor to attract private investors, rebalance the risk-return equation, and expand the availability of market-based funding.

Additionally, **guarantee mechanisms, risk mitigation and collateral funds** are pertinent instruments designed to unlock investments, especially in projects with higher perceived risk or in early stages. By offering partial credit guarantees or coverage in the event of default, the public sector is able to reduce the exposure of private financiers, allowing them to participate in operations that they might not have moved forward with had these guarantees not been in place. Structures of this type can be designed to earmark funding to

specific minerals, ensuring that public support acts as a catalyst for new projects in segments that are essential for decarbonization.

Green taxonomies can also be consolidated as an enabling instrument for attracting investments. These seek to establish objective criteria to classify economic activities as sustainable, creating regulatory clarity for investors and financiers. In Brazil, the recently introduced **Brazilian Sustainable Taxonomy (TSB)** follows international standards and incorporates social goals, like reducing regional and gender inequalities. For the mineral sector, this benchmark can increase the attractiveness of sustainable capital, facilitate access to credit lines aligned with ESG commitments and reduce greenwashing risks. By ensuring interoperability with external standards, like those set by the European Union, TSB is also helping to bring Brazil closer to major global flows of green financing.

A combination of public and private sector capital structures and risk instruments is necessary to finance the high-CAPEX, long-term nature of mining projects, especially those aligned with decarbonization and energy transition mineral production. **A crucial condition for Brazil to capture its potential in the sustainable expansion of mining is that it needs to continue to develop a financial environment that understands these specificities.**

Figure 40 – Recent Examples – Funding Enablers

Selected examples: funding for decarbonization projects		
✓	BNDES and Gerdau – Slurry and Tailings Pipelines (Minas Gerais) and Recycling Center (São Paulo) Approved in 2024, the R\$566 million credit helped facilitate road replacement and increased scrap recycling , with emission reduction scopes 1 and 3 estimated at 100,000 ton/year supported through public funding	
✓	CBA – Specific financial funding for sustainability and emission reduction CBA has diversified its financing sources through instruments aligned with ESG criteria, such as green bonds and sustainability-linked loans	
Selected examples: financing for the expansion of mineral production for the energy transition		
✓	BNDES and Vale – FIP Strategic Minerals (2024) Initiated in 2024, FIP includes contributions of R\$250 million from Vale and BNDES with a goal of investing up to R\$1 billion in exploration, R&D and implementation projects for new mines, focusing on up to 20 junior and medium-sized companies	
✓	BNDES and FINEP – Joint Support Plan (2025) Launched in 2025, the Joint Support Plan (PSC) approved 56 projects through a public notice and will coordinate the allocation of R\$45.8 billion (R\$5 billion of direct investments) via combined financial instruments, including a grant for R&D and innovation	
✓	Government of Germany and KfW – KfW Raw Materials Fund Introduced in 2024, the fund will invest €1 billion in mining, processing and recycling projects for critical raw materials , with contributions of €50 to €150 million, prioritizing security of supply for European industry	
✓	Export Finance Agency – Critical Minerals Facility Since 2021, EFA has gone on to provide funding and cover credit risk for strategic projects, such as those involving critical minerals . One of these was the construction of Western Australia's first rare earth refinery for A\$1.25 billion by Iluka Resources	

5.4 Green Premium and Value Chain

Value chain decarbonization is linked to the establishment of market mechanisms that recognize low-carbon mineral products and harmonize incentives throughout the supply chain.

Because the implementation of decarbonization solutions in mining involves extra costs and new technological prerequisites, their viability will heavily rely on the ability to distinguish and gain economic recognition for these products. Consequently, systems for traceability, certification, and MRV (monitoring, reporting, and verification) are necessary to provide transparency and confidence in validating emissions and environmental characteristics.

One key enabler is the establishment of **demand signals and market guarantees for low-carbon products**, which mitigate investor risk and encourage firms to absorb the costs of decarbonization. Green premium initiatives—additional payment for sustainable products—have been discussed in different industry sectors as a way to align incentives along the value chain and allow lower environmental impact solutions to be financially viable.

Finally, **circularity** has become an integral part of this agenda, encouraging waste reutilization and the development of secondary supply chains that lower input costs and ease environmental pressure from the extraction of new resources. Circularity measures can range from the use of tailings in new processes to the development of markets for recycled materials, helping to reduce carbon intensity and increase efficiency in the use of resources.

5.4.1 Accounting and traceability mechanisms

Carbon accounting is the systematic process of measuring, tracking and reporting greenhouse gas (GHG) emissions linked to economic activities, in an effort to fulfill transparency, environmental responsibility and alignment with corporate or public climate goals. Applied to mining, this process covers all stages—from extraction to beneficiation and industrial processes—and is crucial for identifying the main emission points and guiding mitigation strategies.

Effective tracking protocols, supported by data monitoring, ensure that the **information about the origin and carbon footprint of products activities is trustworthy and accessible**. This contributes to managing social and environmental risks and helps prevent disruptions in the global supply chain. Initiatives such as the pilot Carbon Tracing Platform (using blockchain), developed within the World Economic Forum in partnership with major mining companies, demonstrate the technology's potential to ensure transparency from "mine to final product".

Despite these opportunities, challenges persist. Data quality is critical. Measurement systems need to be accurate and auditable so as to prevent distortion or greenwashing. A balance is also needed between the use of global standards and adaptation to the local specificities of the production chain. **Collaboration between companies, governments and civil society, as well as secure data sharing and transparent governance protocols**, are vital conditions for carbon accounting and traceability systems to fulfill their role of legitimizing low-carbon mineral products without becoming bureaucratic or inaccessible.

5.4.2 Circularity

Circularity in mining refers to practices that are intended to help **reduce the generation of waste and the reuse of materials throughout the production chain**. This approach emphasizes the reuse, recycling and recovery of by-products, promoting increased efficiency in the use of resources and mitigating environmental impacts. In Brazil, initiatives like the projects by the Geological Survey to assess the potential for reuse of tailings, or corporate programs that seek to transform waste into inputs for sectors such as civil construction and steel industry, already indicate concrete ways to expand this agenda.

Major companies have developed projects to use iron ore tailings in the production of "sustainable sand", or even to generate part of the production from waste, reducing the exclusive dependence on the exploration of new deposits. These experiences demonstrate that circularity can contribute both to reducing environmental risks—by reducing volumes of stored tailings—and to creating opportunities for revenue and portfolio diversification.

Despite this potential, large-scale adoption still faces significant barriers. **Economic viability** remains one of the main challenges, as material reuse is not always competitive compared to primary ore extraction. This is particularly apparent during periods of favorable international commodity prices. There are also some technological limitations: many solutions for waste beneficiation are still in the pilot phase and lack industrial scale to become economically viable. Another set of barriers is related to **logistics** and the **regulatory framework**. Harnessing tailings requires transportation and processing under safe conditions, which increases costs in remote mining regions with

limited infrastructure. At the same time, Brazilian legislation still does not offer clear parameters for the classification and commercialization of mining by-products, generating legal uncertainty. Finally, **market acceptance** also needs to be reinforced. This involves having quality standards, certifications and traceability systems created that ensure technical and environmental reliability. Only when progress is made in these areas can circularity become established as a structuring practice in the Brazilian mineral sector.

Figure 41 – Recent Examples – Green Premium and Value Chain Enablers

Selected Examples: signaling and assurance of demand		
✓	Vale and Essar – Offtake Agreement for the Green Steel Mega Hub Vale progressed an agreement in 2023 to supply 4 Mt/year of pellets and briquettes to the Essar electric DRI steel hub in Ras Al Khair, Saudi Arabia. This deal guarantees a crucial demand signal for its low-carbon ore	
✓	GM and Lithium Americas – Industrial customer as anchor buyer and shareholder In 2023, GM invested US\$650 million in Lithium Americas on the condition of ensuring 100% of the Thacker Pass mine's phase 1 production (40,000 t/year for 10 years), ensuring demand and enabling the financing of a greenfield project	
Selected examples: traceability, certification and MRV		
✓	CBA – Selo Alenium for low-carbon footprint aluminum Selo Alenium identifies products made with low-carbon aluminum – produced with 100% renewable energy and with a footprint significantly lower than the global average. The certification uses a methodology aligned with the GHG Protocol, is verified by third parties, and provides greater transparency to the value chain	
✓	Dow – Carbon Footprint Ledger In 2024, with support from the Boston Consulting Group, Dow implemented a traceability model that collects real production data (such as energy consumption and raw materials per plant) and records it in an internal digital system (ledger) , allowing it to calculate and report the carbon footprint for each ton of product produced and sold to each customer	
✓	BHP and Circular – Carbon neutral copper with integrated traceability In 2021, through Circular's blockchain platform , BHP tracked copper emissions from the mine in Chile to the Southwire customer in the US, fully offsetting CO ₂ and creating the first "carbon neutral" copper cathode per batch	
Selected examples: development of circular chains		
✓	Vale – reuse of tailings as sand for construction (Brucutu, Minas Gerais) Since 2021, Vale has invested +R\$50 million in R&D in tailings solutions and has already sold more than 2 Mt of sand produced from iron ore. Final product is supplied directly to public works projects , without any modification or adaptation in terms of infrastructure	
✓	Ambipar – urban mining plant in São José dos Campos (São Paulo) Largest urban mining plant in Latin America , with a capacity of 80,000 ton/year and B2B contracts with large generators. Integrates on-site collection, separation and sale, enabling direct economic return with high-value metals such as copper, gold and lithium	
✓	Michelin – recycling of mining tires in Antofagasta (Chile) Since 2024, Michelin has operated an industrial unit for recycling 63" OTR tires , with a capacity of 8,000 ton/year. In line with the global strategy of circular economy , the plant converts the tires into rubber chips and recovers the metallic material, both used as inputs in the production of new tires	
✓	Alcoa – reuse of industrial waste Alcoa has been developing circular economy initiatives to transform waste into valuable inputs. Illustrative cases include the recovery of spent potlining (SPL) , a residue from aluminum smelting, and boiler ash	

5.5 Regulatory-Economic Scenario

The regulatory environment and the associated economic developments are central conditions for the advancement of decarbonization in Brazilian mining by 2050. Public policies have a direct influence on the decision-making processes of mining companies, as well as having an impact on relevant factors in all other groups of enablers described above.

Mining is an activity marked by **long-term, capital-intensive projects that are highly dependent on licensing and legal certainty**. A mine's development cycle can take decades, from prospecting to full operation, and involves significant financial decisions, often tied to long-term commitments to global customers.

In this sense, the improvement of **stable and predictable regulatory frameworks** is vitally important to ensuring the country's attractiveness in light of international competition for investments. **Clarity and speed in project authorization, alongside unambiguous legal and environmental standards**, will directly determine the sector's capacity to both integrate low-carbon innovations and scale up production. As production swells, Brazil's **mineral and territorial diversity** will increasingly require a regulatory framework that is both comprehensive and **capable of addressing regional specificities**, while respecting local environmental and social conditions **for both mining projects and associated infrastructure** (e.g., biofuels, electrification).

In addition, the insertion of Brazil in international markets implies the need for **regulatory convergence with global guidelines and standards**, especially with regard to sustainability, traceability and reduction of greenhouse gas emissions. To this end, two central themes are highlighted: the implementation of the **Brazilian Emissions Trading System (SBCE)** and the definition of methodologies for accounting for **net emissions**. The SBCE is a flagship government initiative to back the productive sector's decarbonization, serving as a **key instrument to facilitate the transition to a low-carbon economy**. The system creates a regulated market in which companies with emissions above established limits need to reduce or offset their surplus, while others will be able to negotiate credits, becoming the **main carbon pricing instrument in the country**. The **accounting of net emissions** seeks to include not only the gross emissions but also the **carbon sequestration** associated with practices like the restoration of degraded areas, which provides more accuracy and legitimacy to a company's climate balance

IBRAM emphasizes in its statements the importance of having a robust **MRV (Measurement, Reporting, and Verification)** system to lend **credibility to the measurement and reporting of emissions**, as well as the clear definition of methodologies for accounting for **net emissions**. It also points to the relevance of transparent rules for the **use of carbon credits (offsets) within the scope of the SBCE**, in order to align Brazil with international best practices and stimulate new investments in low-carbon projects. These topics are addressed in greater depth in the following subsections.

A broader regulatory modernization effort has been underway in recent years, as evidenced by the **growing number of legal tools and programs** aimed at both the mining sector and the energy sector. In the mineral sector, initiatives are emerging that seek to structure the exploration of strategic minerals with greater predictability and attractiveness. In the energy field, policies associated with biofuels, hydrogen and biomethane create conditions for Brazilian mining to incorporate alternative sources of energy into its production and logistics processes. **These advances do not eliminate future challenges, but indicate that the regulatory environment has been gaining strength as a relevant enabler for transforming the sector towards decarbonization.**

5.5.1 Predictability and agility of licensing

The predictability and efficiency of licensing are among the most relevant aspects of the regulatory environment for the future of Brazilian mining. These factors are **directly linked to the ability to transform the country's mineral potential into an effective supply for global chains in a timely manner**, especially in the case of minerals for the energy transition. The implementation of new operations depends on authorization processes that can consistently meet market demands and international commitments to reduce emissions.

A central factor is related to **the predictability of processing deadlines**. The natural complexity of the regulatory process, which involves various stages and spheres of government, can lead to uncertainties for investors and make it difficult to schedule low-carbon projects. Making progress in this aspect involves not only the improvement of standards, but also the strengthening of coordination between federal, state and municipal levels.

It is important to emphasize that, regardless of the search for the improvement of the regulatory structure, **the credibility, the effectiveness of the processes and the commitment of companies to society and the environment** must be preserved as an essential part of the enabler itself. Increased speed in approvals must be coupled with rigorous technical scrutiny.

Mining companies need to fully comply with operational safety standards, socio-environmental risk management protocols, and all regulatory and assumed commitments. In a country with so much territorial and social-environmental diversity, **this balance will be key to making licensing a tool** that can offer legal certainty, social acceptance, stable operations, and conditions that are good for expanding production and adopting low-carbon tech solutions.

5.5.2 Carbon pricing and the Brazilian Emissions Trading System

Carbon pricing is a central enabler for the decarbonization journey. By establishing an economic value for emissions, it earmarks investments and promotes the competitiveness of low-carbon solutions in the mineral sector. This study references projections from the International Energy Agency (IEA) under the Announced Pledges (APS) and Net Zero by 2050 (NZE) scenarios, which suggest amounts between US\$65-125/tCO₂e in 2035 and US\$160–200/tCO₂e in 2050, to define lever adoption levels and projection of mineral expansion for the energy transition.

The advancement of carbon pricing mechanisms has direct implications for the competitiveness of Brazilian mining. The discussion has been underway for some time in Brazil through the **Brazilian Emissions Trading System (SBCE)**, which seeks to align the country with international practices. This system envisions the creation of a regulated carbon credit market where companies with emissions above established limits need to offset or reduce their emissions, while others will be able to trade surpluses of reductions obtained.

In the context of mining, the introduction of a carbon price tends to act as a **catalyst for technological transformation** in various sectors through the increased costs of more emission-intensive processes. This movement stimulates investments in energy efficiency, electrification and renewable sources, but its effects go beyond the national border. Given the

characteristic of Brazilian mining to feed global production chains in sectors such as industry, transport and energy, **the carbon price defined in different countries will play a decisive role** in shaping the demand for lower carbon-intensity minerals, and may consolidate a competitive advantage for Brazil in the supply of strategic inputs.

For carbon pricing to generate effective gains for the industry and the broader Brazilian economy, its design must be well-calibrated to preserve **competitiveness and secure investment in a just and equitable transition**. The adoption of this instrument should be accompanied by technological innovation, increased efficiency and diversification of the energy matrix, in order **to increase Brazil's attractiveness as a supplier of minerals**. Also, border adjustments can play a significant role in avoiding competitive distortions and mitigating the risk of carbon leakage, preserving the conditions for the country to consolidate its position as a key player in the decarbonization agenda.

IBRAM announced in a public statement that **the mining sector supports the creation of the SBCE**, recognizing that the cap and trade model guarantees greater flexibility and efficiency in the emission reduction process. It also emphasizes the importance of establishing a **cooperative process**, involving government, academia, civil society and industry, to ensure legal certainty and reliability to the market from a **balanced and representative technical structure**.

Some of the future challenges include the need for clarity regarding the rules for **monitoring, reporting and verifying** emissions, to ensure credibility to the system. Additionally, regulatory decisions on transition parameters, specifically the **initial emission thresholds and the process for allowance allocation**, will be decisive for ensuring sector predictability and enabling effective long-term planning. This scenario involves carbon pricing through the Brazilian Emissions Trading System being a central enabler that aligns economic incentives with decarbonization goals and promotes greater integration of Brazilian mining with low-carbon global markets.

5.5.3 Accounting for solutions related to both land restoration and carbon sequestration

Net emissions accounting—that is, recording gross emissions net of carbon sequestration through vegetation restoration—has been widely discussed but remains an evolving topic in the corporate sphere. Since 2020, the GHG Protocol has been working on developing the Land Sector and Removals Guidance, which focuses on **systematizing the recognition of carbon reductions and removals**, including those from ecological restoration, land use and removal technologies.

Although it has been available as a draft for pilot testing since 2022, the final version of this guidance has not yet been published. The absence of a benchmark has limited the ability of miners (and other companies) to **officially incorporate carbon sequestration into their inventories**—that is, to robustly account for net rather than gross emissions. Once established, this definition will allow mining companies to incorporate carbon sequestration practices in their reports—formally recognizing the positive impact of actions such as vegetation recovery or reforestation initiatives.

5.6 International Enablers and COP30

Certain enablers stand out for **requiring cross-border collaboration and adherence to internationally recognized standards**. In the context of COP30 in Brazil, these enablers are becoming more important given the unique opportunity to accelerate advances in international governance mechanisms that can strengthen the Brazilian mineral sector and its strategic relevance in the global energy transition.

The following identifies five critical international enablers for Brazilian mining to secure global recognition for its low-carbon efforts, enhance market and investment access, and guarantee that national advantages, such as renewable energy use and forest restoration, are valued in global value chains:

- **Carbon accounting at the product level**

Accounting systems that capture emissions at the product level, focusing on accurate and traceable measurement for every product that is part of the commercial exchange. This practice is essential to allow the recognition of climate differentials, such as the use of biofuels or renewable energy matrix, in regulated markets and international negotiations, increasing the competitiveness of Brazilian mining products.

- **Harmonization of domestic systems with international standard**

Compatibility of domestic carbon accounting systems with international border mechanisms, including the Carbon Border Adjustment Mechanism (CBAM), in order to ensure mutual recognition and avoid trade barriers, facilitating foreign trade in products with lower carbon intensity.

- **GHG Protocol accounting for removals through restoration**

The official inclusion of CO₂ removals from land restoration and rehabilitation within the scope of the GHG Protocol would allow mining companies to account for these efforts in their corporate inventories. This change is essential for enhancing the value of forest restoration and environmental recovery practices, areas in which Brazil has competitive advantages, in addition to increasing the international credibility of the sector's actions.

- **Green taxonomies for mining and supply chains**

Convergence between national and international green taxonomies is essential to ensure that low-carbon mining projects are eligible for sustainable financing and attractive to global investors. This harmonization expands access to capital and integrates Brazilian mining into a global ecosystem of sustainable finance, enabling new investments in clean technologies

- **Global low-emission hydrogen market**

Establishing international certification and trade standards for low-emission hydrogen is strategic for mining, both for the potential for direct use of hydrogen in industrial processes and for the possibility of export. Brazil's role in building the global hydrogen economy could unlock its potential as a cost-effective producer, thanks to its abundant renewable energy resources and capacity to deliver low-carbon hydrogen at scale.

Figure 42 – Recent Examples – Regulatory-Economic Scenario

Selected examples: expansion of mineral production for the energy transition		
✓	PNMCE – National Policy on Critical and Strategic Minerals (Bill 2780/24, pending in the Chamber) <i>Focusing on capital attraction and regulatory strengthening and predictability, the project aims to establish a legal framework with specific governance, official list of strategic minerals, incentive instruments and priority licensing</i>	
✓	European Union – Critical Raw Materials Act (2023) <i>The CRMA sets minimum targets for production, refining and recycling of critical minerals in the EU by 2030 and imposes maximum timelines for licensing strategic projects: 24 months for mining, 12 for industrial plants</i>	
✓	Canada – Critical Minerals Strategy (2022) <i>The national strategy created task force initiatives and, with the "One Project, One Process" guideline, reformed norms to cut regulatory overlap, streamline licensing processes and consultations, and reduce approval times from 10~15 years to 2~7 years</i>	
Selected examples: incentives for alternative fuels		
✓	PNPB – National Program for the Production and Use of Biodiesel (2004) – B14, 2025 <i>Through progressive targets for blending biodiesel with fossil diesel, the policy has facilitated the incremental development of Brazil's biodiesel sector</i>	
✓	RenovaBio – National Biofuels Policy (2017) <i>With +180 million decarbonization credits (CBIOs) traded since 2020, it turns emission reduction into a tradable financial asset</i>	
✓	New Gas Market (Law 14.134/2021) <i>With +20 new authorized agents since 2021, it expands gas and biomethane routes in industrial plants and logistics corridor</i>	
✓	PNH2 – National Hydrogen Program (2022) <i>With 2024 certification, it structures the tracking of renewable H₂ and enables use in industrial and logistical processes</i>	
✓	Fuel of the Future Law (2024) <i>With progressive targets by 2037, it unifies biodiesel, H₂ and biomethane in a regulatory framework with certification and binding targets</i>	
✓	Zero Methane Program (2022) <i>Combines incentives, credit and exemption to encourage increased production and economic viability of biomethane</i>	



06

Appendix

6.1 Sources

Institution	Document	Year of publication	Brief description
IBRAM	Mineral Sector	2024	Historical data and financial projections for the mineral sector
	Construction and Analysis of the Mining Abatement Marginal Cost Curve	2025	Cost references for decarbonization levers
	The critical and strategic minerals at COP30	2025	Overview of challenges and enablers
	Contribution of the mining sector to the G20	2024	Overview of challenges and enablers, perspectives for ECM
	Resilient mining	2021	Overview of challenges and enablers
	Circularity practices in the mineral sector	2024	Case examples in circularity in Brazil
Ministério de Minas e Energia (Ministry of Mines and Energy)	Studies for the National Mining Plan 2050	2023	Production, reserves and projections for Brazil and the rest of the world
	Critical and strategic minerals for the energy transition	2025	Production and reserves of the main critical minerals extracted in Brazil
	Guide for foreign investors in critical minerals in Brazil	2024	Overview of the Brazilian mining process and opportunities
	Sector Plan for Mitigation and Adaptation to Climate Change in Mining	2013	Reference of levers for decarbonization of mining
IEA	The Role of Critical Minerals in Clean Energy Transitions	2022	Key applications of minerals for the energy transition
	Breakthrough agenda report 2024	2024	Projections for growth in mineral volume
	Global Critical Minerals Outlook, Data Explorer	2025	Demand projections for 34 selected minerals
USGS	Mineral Commodity Summaries (USGS)	2024	Global production and reserves of 88 mineral commodities
Climate Trace	Climate Trace	2024	Emissions data by sector
Observatório do Clima (Climate Observatory)	SEEG 12.0	2023	Emissions data by sector
Vale	Vale Integrated Report	2024	Emission values and process-level breakdowns
Wood Mackenzie	Aluminium at a crossroads: synchronising supply growth with decarbonisation	2025	Demand projections for bauxite for energy transition

6.2 Long list of levers evaluated

Category	Mine	Plant
Efficiency and innovation in processes	• Replacement of trucks with conveyor belts • Route optimization in the mine – Digitization for real-time data exchange (digital twin) • Analytics and machine learning for geological data analysis • Use of autonomous equipment • Machine learning to optimize fuel (tire quality, pressure and temperature, road condition monitoring) • Analytics to optimize the use of explosives • Improvement in the mine area to reduce displacement and emissions • Increase truck efficiency • Automate ventilation and pumping systems	• Controlled starts and pumping efficiency • Rewinding old motors • LED lighting (operating at night) • Predictive equipment maintenance • Optimize crushing and grinding equipment for enhanced energy efficiency
Replacement of fuel	• Partial and total replacement of diesel with biofuels (biodiesel, ethanol, biomethane, HVO) • Mixture of gas with diesel (dynamic blending)	• Replacement of diesel generators with liquefied gas • Replacement of diesel generators with bio-oil
Electrification and power-to-X	• Use of hybrid or electric LHD equipment and electric shovels • Implementation of auxiliary traction systems (trolley assist) • Implementation of battery-powered trucks (BEV) • Hydrogen cells for trucks (FCEV) • Use of green ammonia-based explosives	• Replacement of diesel generators with low-carbon hydrogen generators • Replacement of diesel generators with grid power
Renewable energy supply	• Energy contracts (PPAs) with renewable sources • Solar/wind power generation at mine facilities (e.g., roofs, tailings piles) • Batteries for complementary renewable energy storage	
Land use and forests	• Circular Mining and reuse of waste • Forest protection and restoration	

6.3 Assumptions for modeling

Decarbonization levers in the mining sector:

Category	Lever	Mitigation Potential	Adoption 2035			Adoption 2050			Metrics
			Iron	Gold	Bauxite	Iron	Gold	Bauxite	
Replacement of fuels Electrification and power-to-X	Increase in the partial replacement of diesel with biofuels in the fleet without the need for major engine modifications (drop-in – B12 > B25/B30)	15-20% (B12> B25/B30)	100%	100%	100%	0%	0%	0%	Share of the fleet running on B25/ B30 blends
	Adoption of biofuels in the fleet, with total or partial replacement of diesel by higher proportion blends	25%-30% (B25/B30>B50) 95%-100% (B12>B100))	20%	20%	30%	30%	20%	20%	Share of the fleet running on B50 blends (2035) Share of the fleet running on B100 blends (2050)
	Increase in the partial replacement of diesel with biofuels in stationary combustion equipment without the need for major engine modifications (drop-in – B12 > B25/B30)	15-20% (B12> B25/B30)	100%	100%	100%	0%	0%	0%	Share of stationary equipment with B25/B30 B30equipamentos estacionários com B25/B30
	Adoption of biofuels in stationary combustion equipment, with total or partial replacement of diesel by higher proportion blends	25%-30% (B25/B30>B50) 95%-100% (B12>B100)	20%	20%	30%	100%	100%	100%	Share of equip. running on B50 blends (2035) Share of equip. running on B100 blends (2050)
Eletrification and power-to-X	Implement electric shovels and LHDs to replace diesel alternatives with cleaner solutions	100%	0%	30%	10%	60%	80%	50%	Of the fleet
	Implement battery-powered trucks (BEV) to replace diesel alternatives	100%	0%	5%	5%	40%	50%	50%	Of the fleet
	Implementing off-road FCEV trucks to replace diesel vehicles with hydrogen fuel cell alternatives	100%	0%	0%	0%	30%	30%	30%	Of the fleet

	Deploy trolley assist technology in haulage operations, enabling trucks to draw power from overhead lines during ascents and thereby reduce diesel dependency on inclined routes	90 – 100%	15%	15%	10%	35%	40%	15%	Of mines
Renewable energy	Implement solar and wind PPAs to eliminate scope 2 and foster electromobility	100%	80%	30%	30%	85%	50%	50%	Of electricity purchased
	Implement on-site PV solar (ground-mounted or rooftop) to utilize unassigned areas and provide a partial energy supply for the facility	100%	10%	20%	20%	15%	45%	45%	Of demand from the site
Efficiency and innovation in processes	Use of conveyor belts to replace part of the transport done by trucks	60 – 70%	25%	25%	10%	50%	50%	30%	Of mines
	Increase route efficiency (scanning, telemetry and sequencing) and vehicle efficiency (LRR tires and engines) to reduce diesel consumption	5%	70%	50%	50%	90%	100%	100%	Optimized dispatch fleet
	Optimize crushing and grinding equipment for enhanced energy efficiency	5 – 10%	30%	30%	30%	90%	90%	90%	Optimized crushers

Decarbonization levers in the iron chain:

Category	Lever	Mitigation Potential	Adoption 2035	Adoption 2050	Metrics
Products for steelmaking	Upgrade or scale existing pelletizing facilities to supply DR-grade pellets—critical for supporting DRI-EAF routes using natural gas or green hydrogen	40-90% (B12> B25/B30)	~10%	~10%	% of Fe exported in DR-grade pellets
	Apply cold agglomeration for briquette formation, converting iron ore fines without the need for sintering or pelletizing, enabling use in DRI routes or as partial feed in blast furnaces	25%-30% (B25/B30>B50) 95%-100% (B12>B100))	~1%	~2%	% of Fe exported in DR-grade pellets
Long-haul shipping Pelletizing	Prioritize contracts that require energy efficiency systems on ships such as slow steaming, anti-friction coatings, use of sails, etc.	65 – 90%	30-60%	100%	Volume transported in dual-fuel/low-carbon ships
	Prioritize contracts that require energy efficiency systems on ships such as slow steaming, anti-friction coatings, use of sails, etc.	5 – 30%	30-70%	100%	Volume transported in dual-fuel/low-carbon ships
	Implement integrated logistics planning (port-mine-ship), reducing port waiting time, increasing ship occupancy rates, backhauling percentage and avoiding suboptimal departures	2 – 5%	10%	50%	% of mines
Pelotização	Use biocarbon or charcoal during pelletizing to partially replace coal in the combustion process	95 – 100%	7%	30%	Replacement of mineral coal by biocarbon/ charcoal
	Use biofuels as bio-oil or biomethane as a substitute for natural gas in pelletizing furnaces	95 – 100%	5%	20%	Replacement of NG with biofuels
	Use CO ₂ capture in furnaces or boilers to eliminate emissions via injection into a geological reservoir	80 – 90%	0%	100%	Of chimneys
	Use low-carbon hydrogen as a heat source in pelletizing furnaces, partially or totally replacing natural gas	100%	0%	15%	Replacement of NG with low-carbon hydrogen
	Implement solar and wind PPAs to eliminate scope 2 and foster electromobility	100%	100%	100%	Of electricity purchased

6.4 Details of mineral production projections for the energy transition

6.4.1 Bauxite

Wood Mackenzie projections indicate a **CAGR of 0.7% for global demand** in the Country Pledges scenario, adopted as the **lower range** of the projection

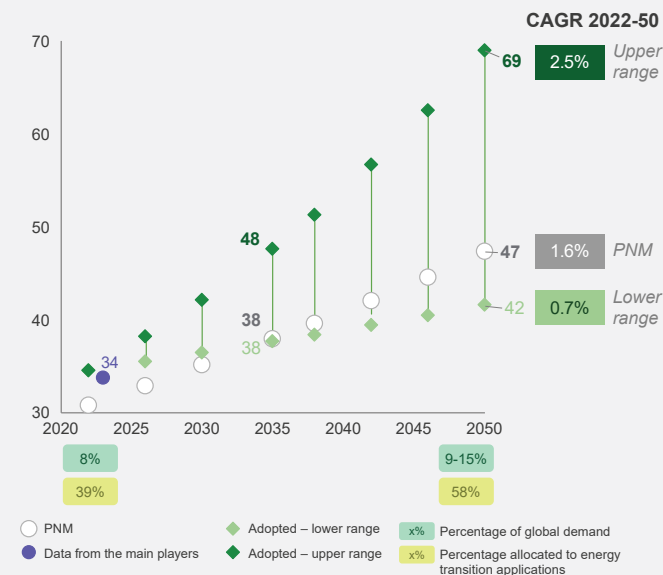
In the **Net Zero** scenario, demand projection for energy transition has a **CAGR of 2.5%**, used as a parameter for the **upper range** of the estimate

PNM projections, with a CAGR of **1.6%**, remain **within the projected range** over the long term

Data available from the main players add up to production of **~34 Mton of bauxite in 2023**

- **MRN**: projects to maintain current production of ~12.7 Mt bauxite
- **Norsk Hydro (Paragominas)**: current production of ~11 Mt of bauxite, with no plans to expand capacity
- **Alcoa**: current production of ~6.3 Mt bauxite, with no plans to expand capacity
- **CBA**: current production of ~1.9 Mt of bauxite
- **TGM**: current production of ~1.6 Mt of bauxite

Brazilian production of bauxite (Mton. 2022-2050)



Note: Considering that 5 tons of bauxite are needed to produce 1 ton of aluminum

Sources: USGS, Wood Mackenzie, Brasil Mineral, Studies for PNM 2050, Companies' reports

6.4.2 Manganese

PNM projection indicates **CAGR of 4.0%**, applied to current production to calculate the **upper range** of the projected range¹

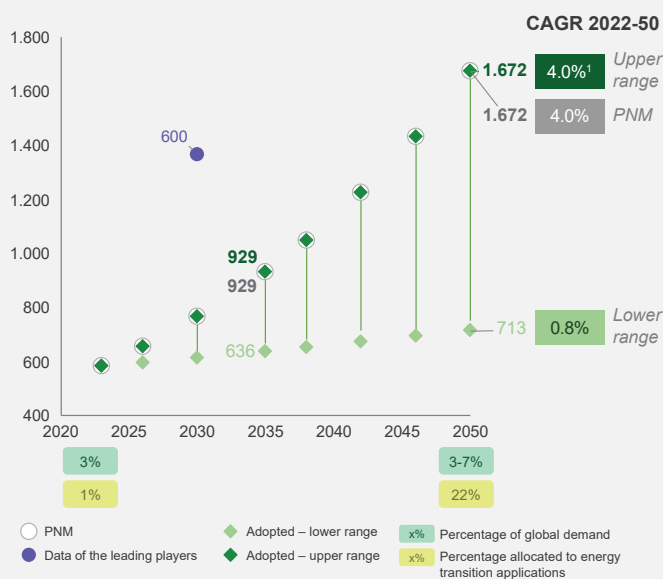
The Net Zero Scenario projects an annual growth rate of 14% for energy transition demand. This figure was excluded from defining the final range, given that the share of production dedicated to these applications is relatively insignificant (~1%)

IEA indicates a **CAGR of 0.8%** for **global demand** in the Announced Pledges scenario, adopted as the **lower range** of the projection and 0.9% in the Net Zero scenario (within the range)

Initiatives by leading players to increase their production capacity suggest production of ~1365 kton of manganese by 2030, significantly more optimistic than the upper range adopted

- **Buritirama**: goal to reach 2.8 Mton of manganese ore (~1.1 Mt of metallic manganese²) without a defined public deadline – 2030 was adopted as the target year
- **LHG Mining (J&F)**: production projections for 2030 not available – current production was adopted of 450 kton of manganese ore (~180 kton of metallic manganese²)
- **Nexus**: production projections for 2030 not available – current disclosed capacity was adopted of 163 kton of manganese ore (~65 kton of metallic manganese²)

Brazilian production of manganese (kton contained. 2022-2050)



1. The CAGR of the PNM projection was applied to the production disclosed by the USGS in 2023 (in line with the 2025 EPE report) 2. Considering a content of 40% metallic manganese

Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies

6.4.3 Copper

PNM projection indicates **CAGR of 4.4%**, corresponding to the upper range of the projected range

IEA's Announced Pledges Scenario indicates a **CAGR of 1.5%** for global demand, adopted as the **lower range**

In the IEA **Net Zero** scenario, demand projections have CAGRs of **1.7% (global)** and **3.7% (energy transition)**, both within the projected range

The leading players' expansion projects are targeting production of **~419 kton of copper by 2030, within the range adopted**

- **Vale:** with production of 350 kton of copper in 2024 (with ~270 kton in Brazil), it intends to reach 420~500 kton in 2030¹
- **Lundin:** average production of ~20 kton of copper in the last 4 years is expected to grow ~30% by 2030
- **Vale Verde Mining:** production projections for 2030 not available – current production of ~20 kton of copper was adopted from the Serrote mine
- **Ero Group:** projections indicate production of ~18 kton in 2030

Brazilian production of copper (kton contained, 2022-2050)



1. The same percentage of global production in Brazil was considered to calculate Vale's 2030 target

Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies

6.4.4 Zinc

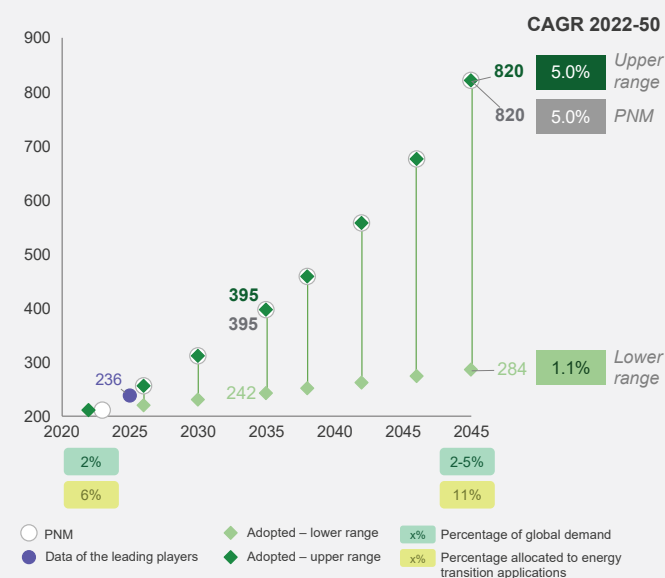
PNM projection indicates **CAGR of 5.0%**, applied to current production to calculate the **upper range** of the projected range

IEA indicates a **CAGR of 1.1% for global demand**, both in the Announced Pledges scenario and in Net Zero, the value adopted for the **lower range** of the projection

Data from the leading players in Brazil indicate production of **~236 kton of zinc in 2025**, in line with the range adopted

- **Nexa:** with expansion in Aripuanã, it is expected to produce ~216 kton of zinc by 2025
- **Santa Elina Mining:** projections for 2025 not available – a volume of 20 kton was used, disclosed in 2021¹

Brazilian production of zinc (kton contained, 2022-2050)



1. Considering national production of ~160 kton (Mineral Summary) and Nexa production of 140 kton

Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies

6.4.5 Silicon

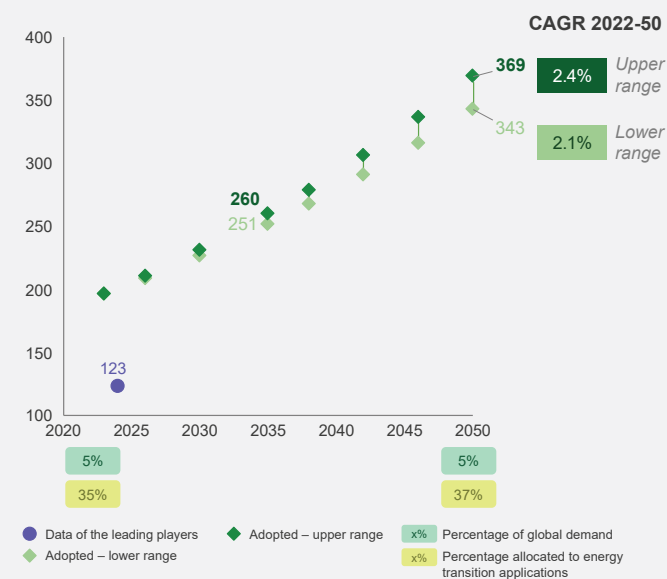
IEA's Announced Pledges Scenario indicates a **CAGR of 2.1%** for global demand, adopted as the **lower range**

Under the **Net Zero** scenario, projected demand for the energy transition grows at an annual rate of **2.4%**, which defines the **upper range** of the interval; global demand projections show a CAGR of 2.2%, falling within the adopted range

Data available from the leading players in the market add up to production of **~123 kton of silicon in 2024**

- **Liasa**: in 2020, announced investment to increase productive capacity to ~83 kton by 2024
- **Minasligas**: production projections not available – disclosed capacity of 40 kton silicon metal was adopted
- **Rima** (largest silicon producer in Brazil¹): volume data not publicly released

Brazilian production of silicon metal (kton contained. 2022-2050)



Note: PNM 2050 plan does not include any projections for silicon production 1. According to the company's website

Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies

6.4.6 Niobium

IEA's **Net Zero and Announced Pledges** scenarios indicate **CAGR of ~1.3%** for global demand of niobium

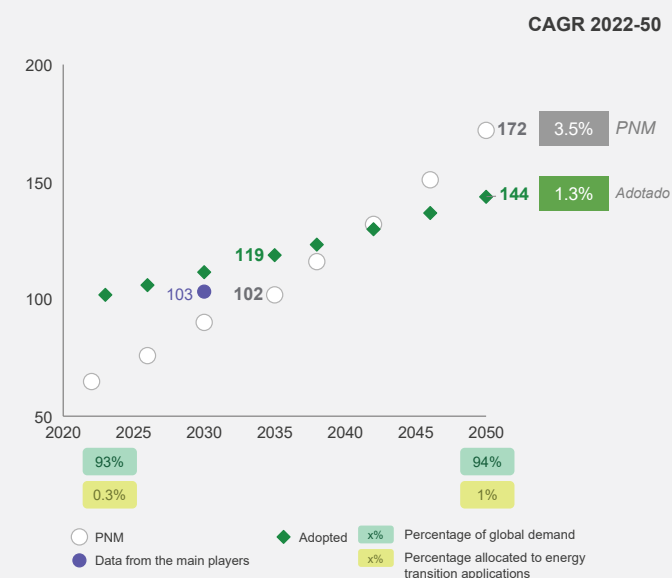
Under the **Net Zero** Scenario, demand growth for **energy transition applications hits 7%**. This figure was not factored into the projections, given the volume's low impact on total demand (**0.3%**)

PNM projections (2022) are derived from a significantly lower volume compared to those of USGS (2023) because they were developed in a context of lower national production. In addition, Brazil is expected to **produce more niobium than the world requires, according to PNM projections for 2050**. Based on that, the CAGR PNM of 3.5% was not used in the projection adopted

Data available from the leading players in Brazil indicate production of **~103 kton of niobium in 2030**, closer to the volume adopted by this study

- **CBMM**: projections not available – current capacity of 150 kton of ferroniobium was adopted (~90 kton of niobium¹)
- **CMOC Brazil**: projections not available – current production of 10 kton of niobium was adopted
- **Taboca**: the potential to increase production from 1.6 to 3.2 kton per year of metallic niobium by 2030 was considered

Brazilian production of niobium (kton contained. 2022-2050)



1. Considering a niobium content of 60% in FeNb

Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies

6.4.7 Nickel

IEA's **Announced Pledges** scenario indicates a **CAGR of 3.0%** for global demand, adopted as the **lower range**

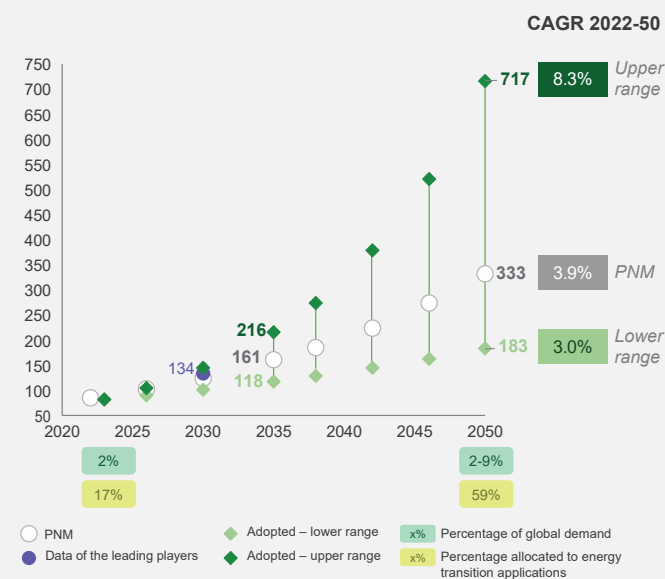
In the **IEA Net Zero** scenario, demand projection for energy transition has a CAGR of **8.3%**, used as a parameter for the **upper range** of the estimate

PNM projections, with a CAGR of 3.9%, remain **within the projected range** over time

Expansion projects by the leading players add up to production of **~134 kton of nickel by 2030**, in line with the range adopted

- **Vale:** expansion in Onça Puma is expected to increase Vale's annual production from 27 kton to 42 kton of nickel by 2030
- **MMG** (operation sold by Anglo American): projections for 2030 not available – guidance of ~39 kton was adopted for 2025
- **Wave Nickel Brasil:** projections for 2030 not available – Niquelândia plant capacity of 20 kton per year was adopted
- **Brazilian Nickel:** projections for 2030 not available – expected capacity of ~18 kton of nickel per year was adopted with the expansion of the Piauí Nickel Project
- **Atlantic Nickel:** projections for 2030 not available – disclosed capacity of 15 kton per year was adopted

Brazilian production of nickel (kton contained, 2022-2050)



Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies

6.4.8 Graphite

IEA's **Announced Pledges** Scenario points to a **CAGR of 3.5%** for global demand, adopted as the **lower range**

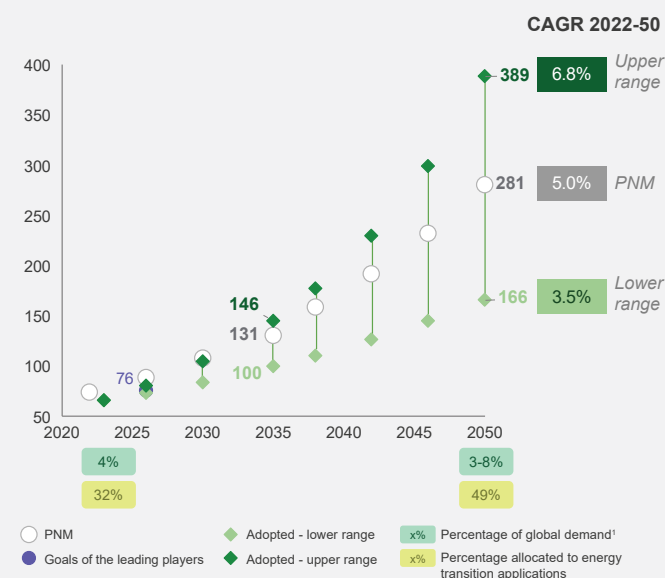
In the **IEA Net Zero** scenario, demand projection for energy transition has a CAGR of **6.8%**, used as a parameter for the **upper range** of the interval

PNM projections, with a CAGR of 5%, remain **within the projected range** over the long term

Production by the leading players indicates **~76 kton of graphite by 2026**, within the range adopted

- **Nacional de Grafite:** production projections not available – current production of 70 kton of graphite per year
- **Graphcoa:** targets a capacity of 5.5 kton per year by the end of 2026

Brazilian production of graphite (kton contained, 2022-2050)



1. Considering natural graphite

Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies

6.4.9 Vanadium

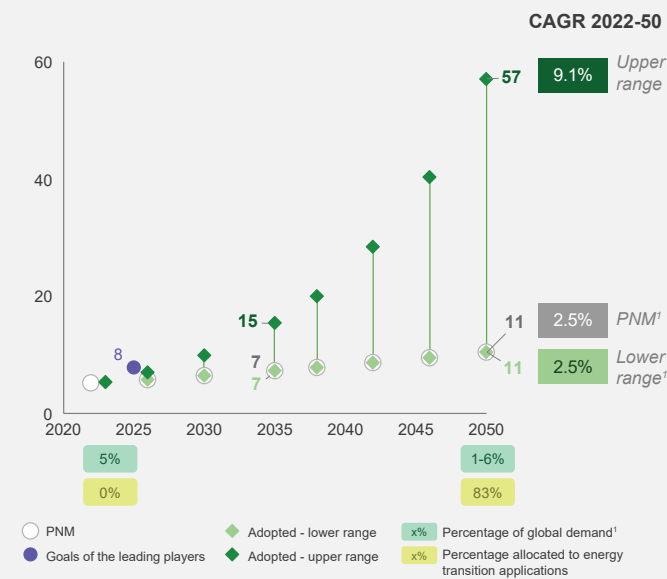
PNM projections indicate **CAGR of 2.5%**, applied to current production to calculate the **lower range** of the projected interval¹

IEA's **Net Zero** Scenario indicates a CAGR of **9.1%** for global demand, applied to the **upper range** of the estimate; the growth rate of energy transition applications was not used, since current demand is zero

Data from the leading players indicate production of **~8 kton of vanadium in 2025**

- **Largo Inc.:** guidance of 9.5-11.5 kton of V_2O_5 for 2025 (the most optimistic volume was adopted, corresponding to ~6.4 kton of metallic vanadium²)
- **Jangada Mines:** looking to achieve a volume of ~1.5 kton per year with the Pitombeiras^{2,3} project
- **BMIX** (linked to Brazil Minerals): acquired rights to develop a vanadium project in Piauí in 2013, but there were no production projections available yet

Brazilian production of metallic vanadium (kton contained, 2022-2050)



1. The CAGR of the PNM projection was applied to the production announced by the USGS in 2023 (5.42 kton of vanadium contained in 2023); PNM starts from a production volume of 14 kton in 2022, reaching 28.5 kton in 2050 (still within the projected range) 2. Considering 56% of metallic vanadium in V_2O_5 3. Considering 23.5 kton of V_2O_5 distributed over the 9-year life of the mine

Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies

6.4.10 Metallic Lithium

PNM projections point to accelerated growth by 2030, with production stabilization from 2040, **converging to the lower range in the long term (CAGR of 4.9% in the 2022-2050 period)**

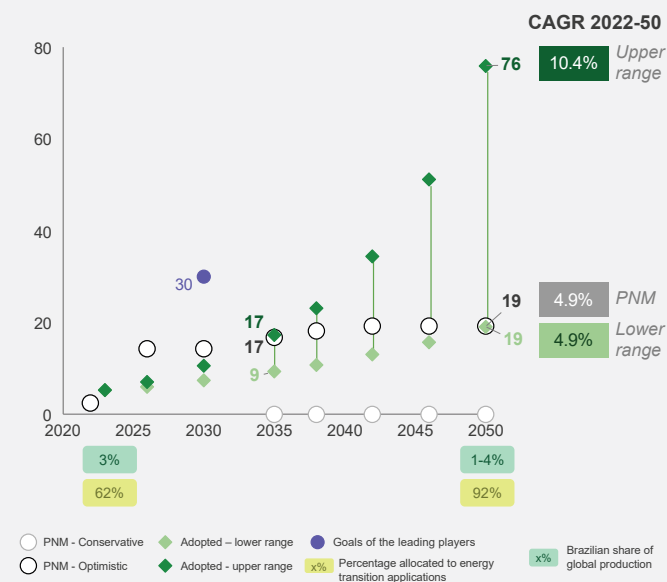
Application of the **CAGR of 10.4% of the IEA** for demand in energy transition results in a significantly more **optimistic** scenario, with production topping 76 kton

IEA **Announced Pledges** scenario Indicates **8.1% CAGR** for global demand, **within projected range**

Expansion projects by the leading players suggest production of **~30 kton of metallic lithium by 2030**, a significantly more aggressive volume than projections adopted

- **Sigma Lithium:** projections for 2030 not available – projection of 770 kton of spodumene for 2027 (equivalent to ~20 kton of Li^+)
- **AMG:** projections for 2030 not available – current capacity of 130 kton of spodumene (~3.3 kton of Li^+)
- **Atlas Lithium:** projections for 2030 not available – a goal was adopted to exceed 150 kton per year of spodumene in 2025 (~3.8 kton of Li^+)
- **CBL:** boasting an annual production of 1.5 kton LCE, added to 42 kton of spodumene concentrate (~2.7 kton of Li^+), it announced investments to double its capacity by 2030

Brazilian production of metallic lithium (Li) (kton contained, 2022-2050)



1. Considering 5.5% Li_2O in concentrated spodumene, 19% metallic lithium in Li_2CO_3 (or LCE) and 47% metallic lithium in Li_2O

Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies, Brasil Mineral

6.4.11 Lithium

PNM projections point to accelerated growth by 2030, with production stabilization from 2040, **converging to the lower range over the long term (CAGR of 4.9% in the 2022-2050 period)**

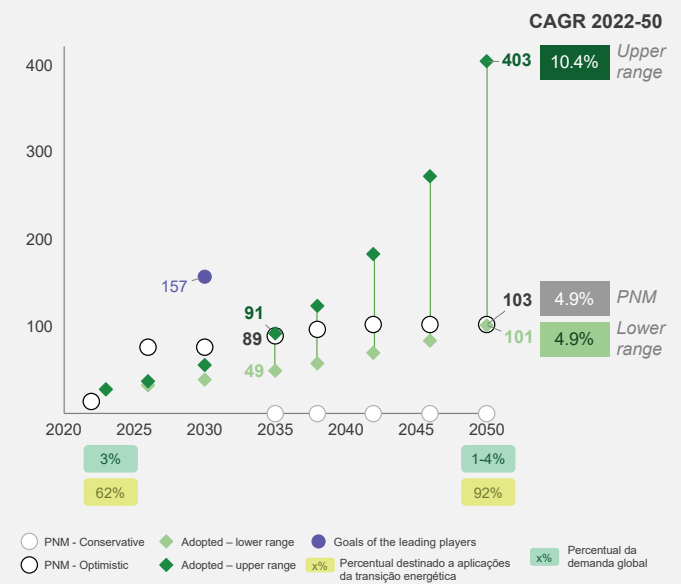
Application of the **CAGR of 10.4% of the IEA** for demand in energy transition results in a significantly more **optimistic** scenario, with production reaching 76 kton

IEA **Announced Pledges** scenario indicates **an 8.1% CAGR** for global demand, **within the projected range**

Expansion projects by the leading players indicate production of **~157 kton of LCE by 2030**, a significantly more aggressive volume than projections adopted¹

- **Sigma Lithium:** projections for 2030 not available – projection of 770 kton of spodumene was adopted for 2027 (equivalent to ~105 kton of LCE)
- **AMG:** projections for 2030 not available – current capacity of 130 kton of spodumene was adopted (~18 kton of LCE)
- **Atlas Lithium:** projections for 2030 not available – a goal was adopted to exceed 150 kton per year of spodumene in 2025 (~20 kton of LCE)
- **CBL:** boasting an annual production of 1.5 kton LCE, added to 42 kton of spodumene concentrate (~14kton of LCE in total), it announced investments to double its capacity by 2030

Brazilian production of lithium (LCE) (kton contained, 2022-2050)



1. Considering 5.5% Li₂O in concentrated spodumene, 19% metallic lithium in Li₂CO₃ (or LCE) and 47% metallic lithium in Li₂O
Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies, Brasil Mineral

6.4.12 Tantalum

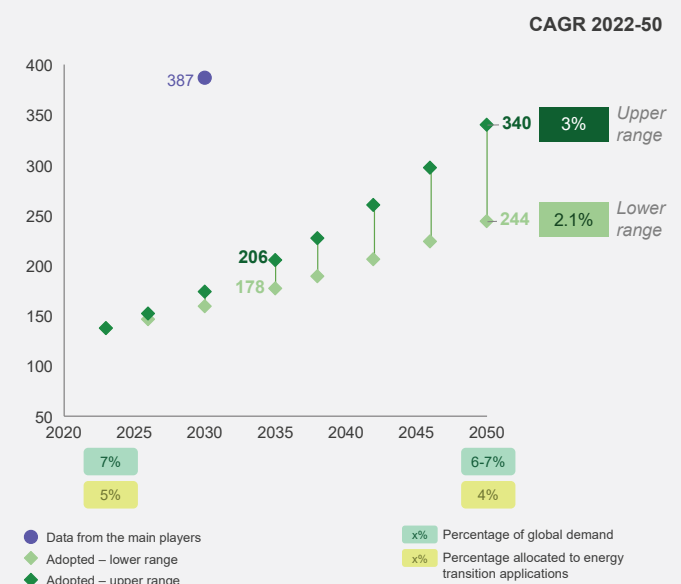
In all scenarios, IEA points to a **CAGR of 3.0%** for global demand, adopted as the **upper range** of the interval

In the IEA **Net Zero** scenario, demand projection for energy transition has a CAGR of **2.1%**, used as a parameter for the **lower range** of the estimate

Available data from producing companies indicate a volume of **~387 ton of tantalum by 2030**

- **Taboca:** the potential to increase production from 160 to 320 tons per year of metallic tantalum by 2030 was considered
- **AMG:** a disclosed capacity of 600,000 lbs of tantalum concentrate (equivalent to ~67 ton of metallic tantalum¹) was considered

Brazilian production of tantalum (kton contained, 2022-2050)



Note: PNM starts production of 380 kton of tantalum ore in 2022 (equivalent to 37~100 kton of metallic tantalum, depending on the Ta₂O₅ content), far from the scale disclosed by the USGS and current players 1. Considering an average content of 30% of Ta₂O₅ in the concentrate and a proportion of 82% of metallic Ta in the oxide.

Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies

6.4.13 Rare Earths

Projects announced add up to a total production of **~1.4 kton of rare earths by 2030**

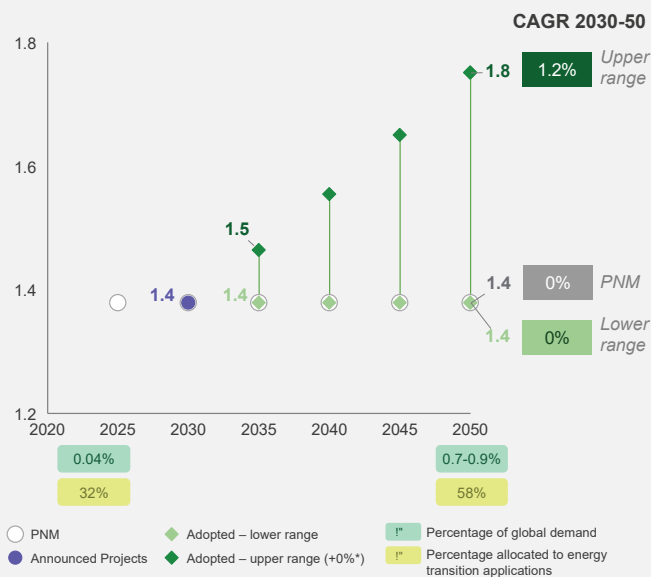
- **Serra Verde Mining:** started its commercial production in 2024 and plans to reach ~0.86 kton of rare earths¹ (Nd, Pr, Dy, Tb) per year in 2030²
- **Meteoric Resources (Caldeira project):** projection for 2030 not available – disclosed capacity of ~0.52 kton³ of rare earths¹ (Nd, Pr, Dy, Tb) per year was adopted

Given the low volume of current production and the announced projects, definition of the **upper range** considered:

- As a starting point, the sum of the volumes foreseen in the **announced projects** (by 2030)
- For 2050, a projection based on the **CAGR of demand related to the energy transition** in the 2030-2050 period (**1.2%**)

PNM projection **does not foresee production growth** from 2025 to 2050, adopted as a **lower range over the long term**

Brazilian production of rare earths (kton contained, 2022-2050)



Note: In this study, the same metals as the IEA projections are considered: praseodymium (Pr), neodymium (Nd), terbium (Tb) and dysprosium (Dy), corresponding to ~85% of the market value of rare earth oxide 1. Considering rare earth oxides with the following composition: 13.2% Nd₂O₃, 4.4% Pr₆O₁₁, 1.9% Dy₂O₃, 0.6% Tb₄O₇ 2. Announced production projection of 10 kton of rare earth oxide 3. Announced production projection of 6 kton of rare earth oxide. Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies

6.4.14 Cobalt

Announced projects add up to a total production of **~7.9 kton of cobalt**

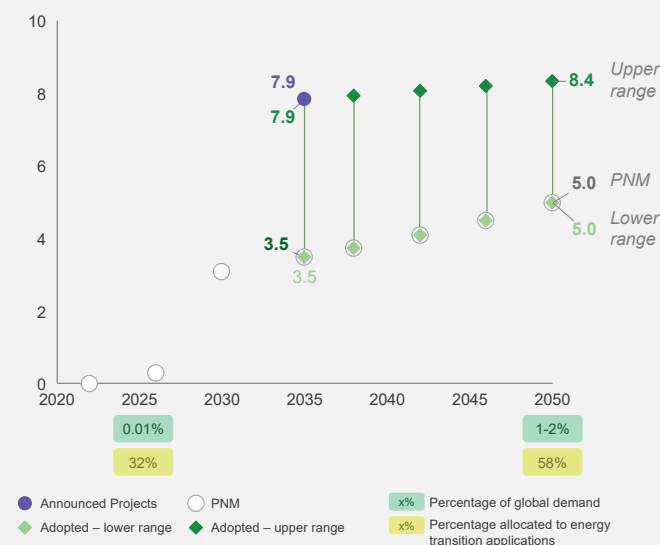
- **Atlantic Nickel:** projections not available – current production of 0.25 kton per year
- **Horizonte Minerals PLC (Projeto Vermelho):** start of operation scheduled for 2027, with the goal of reaching 1.3 kton
- **Brazilian Nickel (Piauí Nickel Metals):** first production scheduled for 2028, with a goal of reaching 0.9 kton of cobalt
- **Minmetals (Projeto Jacaré):** production estimated by Anglo American at 5.4 kton/year¹

Given the low volume of current production and the announced projects, definition of the **upper range** considered:

- As a starting point, the sum of the volumes foreseen in the **announced projects** (by 2035)
- For 2050, a projection based on the **CAGR of demand related to the energy transition** in the 2035-2050 period (**0.4%**)

PNM shows **accelerated growth by 2030 and CAGR of 2.4%** by 2050, adopted as a **lower range over the long term**

Brazilian production of cobalt (kton contained, 2022-2050)



1. Schedule not available, so start of production in 2035 was adopted

Sources: USGS, IEA, Studies for PNM 2050, Reports from the companies

