TECHNICAL REPORT

Brazil's role in the Global Critical and Strategic Minerals Agenda

Projected demand and Brazil's potential contribution in the energy transition

The results of the project "Brazil's Role in the Global Agenda for Critical and Strategic Minerals", developed by CEBRI and IBRAM, reflect the research and projections carried out by Cenergia, CETEM and SGB. They do not not necessarily reflect the individual views of the entities that participated in the Program and may not consider other work these entities are developing.
The recommendations presented should be considered in light of policies, ongoing work, and analyses on critical and strategic minerals carried out by the relevant entities or institutions. The analyses and policy recommendations in this report are not exhaustive and are subject to review for validity and consistency with the regulatory, technical and policy frameworks of the industries involved and in the specific context of Brazil.

December 2025

Technical report

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DEVELOPED BY

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IBRAM MINERAÇÃO DO BRASIL

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SGB SERVIÇO GEOLÓGICO DO BRASIL

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Summary

About the project

The project was initiated in 2024 to provide an analysis of domestic demand for, and potential supply of, energy transition minerals. Its aim is to analyze the role Brazil can play in the critical and strategic minerals (CSM) agenda, considering the importance of CSM for the low-carbon economy and their current geopolitical significance.

This initiative is led by the Brazilian Center for International Relations (CEBRI), in cooperation with the Brazilian Mining Association (IBRAM), Cenergia (Coppe/UFRJ), the Mineral Technology Center (CETEM) and the Geological Survey of Brazil (SGB). The project was implemented in partnership with the Institute for Climate and Society (iCS) and the Energy Research Company (EPE), with sponsorship from BHP and Vale, and institutional support from BMA Advogados.

The analysis is based on three core premises, as follows:

(i) Brazil boasts undeniable potential for strategic integration into global CSM supply chains;

(ii) International competition for CSM has intensified, largely driven by the energy transition, and also by the defense and digital transformation sectors;

(iii) The geographic concentration of CSM supply and processing poses geopolitical and trade risks, underscoring the importance of diversifying supplier countries and strategic partners. This creates a unique opportunity for Brazil to position itself as a trusted global supplier.

Through an analysis involving different perspectives and stakeholders, this report investigates the potential impacts of the technological pathways for emissions mitigation on mineral demand in Brazil, maps Brazil's mineral potential in response to both domestic and global needs, and explores the broader implications of this transition for key industries and their supply chains. These results seek to:

1

Support
Brazil's strategic planning;

2

Assist
in the development of public policies aimed at attracting investments, bolstering domestic supply, and promoting sustainable development;

3

Foster
Brazil's integration into global value chains.

The supply-side analysis primarily drew on inputs from CETEM and SGB to estimate Brazil's mineral potential to meet the demands of the energy transition. Our evaluation of mineral supply considered in-place resources (mineral endowment), i.e., reserves whose extraction is deemed technically and economically feasible, as well as the minerals produced at the midstream, downstream, and secondary material recovery stages.

The demand-side analysis relied primarily on inputs from the Cenergia (Coppe/UFRJ) to project mineral demand for key energy converters in a scenario where Brazil successfully meets its nationally determined contribution (NDC) targets[1], ultimately achieving greenhouse gas (GHG) neutrality by 2050. The reference is the "Brazil Transition" scenario proposed in the Energy Transition Program (PTE2), which utilized the BLUES (Brazilian Land-Use and Energy Systems) integrated assessment model to analyze energy supply and demand, and land use. The BLUES integrated model was designed to comprehensively capture the interrelations in Brazil between land use, energy systems, and greenhouse gas emissions. See Appendix A for methodological details.

This technical report was prepared based on the cross-analysis of the results obtained, complemented by additional work and contributions from experts and organizations[2]. It summarizes the key findings on domestic CSM supply and demand, and identifies bottlenecks and opportunities for Brazil.

The analyses and recommendations in this report are forward-looking visions and interpretations that are not derived only from modeling results. They

1. This scenario envisions a reduction of approximately 50% in net GHG emissions by 2030 compared to 2005 levels, and achieving zero net emissions by 2050.

2. The development of this study involved the participation of various stakeholders and institutions through consultations and closed-door meetings, contributing essential analyses and insights to its execution. Notable participants included project sponsors BHP and Vale, and also BMA Advogados, IBRAM, iCS, ANM, BloombergNEF, C3, ClouderVista, ConDET, E+ Transição Energética, Government of Goiás, Ministry of Mines and Energy (MME), Simineral, Systemiq, APCO.

may also draw on data from partner organizations, as well as evidence and projections regarding the current state of the energy transition. As such, they aim to go beyond quantitative scenarios and to incorporate complementary analyses so as to offer a broader perspective on Brazil's role in the critical and strategic minerals agenda.

This report provides an overview of the international landscape in which Brazil is positioned and offers public policy recommendations, along with strategies for investment and international cooperation.

List of abbreviations

AAM - Active Anode Material

AFC - Alkaline Fuel Cell

BDC - Brushed DC Motor

BLDC - Brushless DC Motor

BPS - Bromine Polysulfide

CBA - Brazilian Aluminum Company

CBMM - Brazilian Metallurgy and Mining Company

CBPM - Bahia Mineral Research Company

CFEM - Financial Compensation for the Exploration of Mineral Resources (royalties)

CIGS - Copper Indium Gallium Selenide (Thin films of copper, indium, gallium and selenium)

CMOC - China Molybdenum Company

CNM - National Mining Company

CRMA - Critical Raw Materials Act (EU)

CSM - Critical and Strategic Minerals

CTAPME - Technical Committee on Mineral and Energy Policies

DFIG - Doubly-Fed Induction Generator

DRC - Democratic Republic of Congo

EESG - Electrically Excited Synchronous Generator

EESM - Electrically Excited Synchronous Motor

EPE - Energy Research Company

ESG - Environmental, Social and Governance

EU - European Union

GHG – Greenhouse Gases

IAC - Ion Adsorption Clays

IEA - International Energy Agency

IM - Induction Motor

IOCG - Iron Oxide Copper Gold (Iron Oxide, Copper and Gold Deposit)

IPEA – Applied Economic Research Institute

LCO - Lithium Cobalt Oxide

LCOE - Levelized Cost of Energy

LFP - Lithium Iron Phosphate

LMO - Lithium Manganese Oxide

LTO - Lithium Titanate Oxide

MCFC - Molten Carbonate Fuel Cell

MME - Ministry of Mines and Energy

MREC - Mixed Rare Earth Concentrate

MREO - Magnetic Rare Earth Oxides

MRN - Rio do Norte Mining

NCA - Nickel Cobalt Aluminum

NDC - Nationally Determined Contribution

NIB - New Brazilian Industry Program

NMC - Nickel Manganese Cobalt

NPV - Net Present Value

PAFC - Phosphoric Acid Fuel Cell

Pal - Pressure Acid Leach

PCBs - Printed Circuit Boards

PDAC - Prospectors & Developers Association of Canada

PDGMTM - Twenty-Year Geology, Mining and Mineral Transformation Plan

PEMFC - Proton Exchange Membrane Fuel Cell

PLANAVEG - National Plan for the Recovery of Native Vegetation

PLANTE - National Energy Transition Plan

PMSG - Permanent Magnet Synchronous Generator

PMSM - Permanent Magnet Synchronous Motor

PNM - National Mining Plan

PTE - Ecological Transformation Plan

PTE-2 - Second Phase of the Energy Transition Program

PWR - Pressurized Water Reactor

REEs - Rare Earth Elements

REO - Rare Earth Oxides (REE Oxides)

ROM - Run of Mine (Raw Ore Extracted)

SEDEX - Sedimentary Exhalative Deposit

SGB - Geological Survey of Brazil

SOFC - Solid Oxide Fuel Cell

SQIG - Squirrel Cage Induction Generator

SRM - Switched Reluctance Motor

SX-EW - Solvent Extraction - Electrowinning

TGC - Total Graphitic Carbon

TREO - Total Rare Earth Oxides

UNECE - United Nations Economic Commission for Europe

USA - United States of America

USGS - United States Geological Survey

VMs - Volcanogenic Massive Sulfide

VRFB - Vanadium Redox Flow Battery

WRIG - Wound Rotor Induction Generator

Executive summary

This report is the result of a partnership between CEBRI, IBRAM, Cenergia (Coppe/UFRJ), CETEM and SGB. The primary objective of this project is to evaluate the impact of the energy transition on the demand for critical and strategic minerals (CSM) in Brazil by 2050, while also estimating the country's ability to supply these minerals to the global market. The analysis combines: i) the projected demand for materials, derived derived from the "Brazil Transition" scenario developed by CEBRI's Energy Transition Program, which is aligned with Brazil's NDC (GHG neutrality by 2050); and ii) an assessment of Brazil's mineral supply. The goal is to guide public policies and investments to position Brazil as a reliable and competitive supplier in global value chains - identifying synergies between CSM supply and demand, so that Brazil can capitalize on opportunities to develop its production chain. In other words, the aim is not to focus solely on mineral extraction, but also to identify opportunities for advancement in beneficiation and processing activities, and in higher value-added products.

Context

The energy transition increases the material intensity of energy and mobility systems. In this context, "critical" refers to minerals that are essential and at risk of supply disruption, while "strategic" refers to minerals with economic significance for which a country presents competitive advantages. Brazil does not have a formal list of "critical" minerals but does maintain a list of "strategic" minerals (MME/2021), which includes, among others, copper, nickel, niobium, graphite, lithium, and rare earth elements (REE). Currently, there is a pronounced geographic concentration in extraction activities and, even more so, in refining, with China maintaining a dominant position in graphite and REE, and Indonesia leading in nickel. This scenario underscores the importance of diversifying global supply chains and establishing reliable alternative suppliers.

Methodology

CETEM estimated the mineral supply potential based on data from the Geological Service of Brazil (SGB) and various other sources, including field surveys, internal reports, research on mining industry company portals, and official documents such as reports and publications from regulatory agencies.

Supply was estimated using data on endowment, resources, reserves, and production, complemented by a value chain perspective encompassing the upstream, midstream and downstream stages, as well as recyclability.

The projected demand for materials centered on identifying major energy converter groups for 2025-2050 based on BLUES modeling results for the Brazil Transition scenario, from Phase Two of the Energy Transition Program (see Appendix A). Material intensities and end-of-life replacement dynamics were applied to each converter (solar, wind, batteries, engines, fuel cells, nuclear) and the most promising technology converter families were then selected through a review of technical and scientific literature, guided by technical, economic and environmental criteria. The demand for materials was subsequently projected (see Appendices A and B).

Brazilian supply: potential and value chains

Brazil combines volume, diversity and geological quality:

- **Graphite:** Found in the Bahia-Minas and Ceará provinces; graphitic carbon content of ~105 Mt; critical input for batteries in electric vehicles and storage systems.
- **Rare Earth Elements (REE - Nd, Pr, Dy, Tb):** Pioneer ionic clay operation (Serra Verde, GO); estimated total rare earth oxides (TREO) of ~5.5 Mt in reported projects; useful for the production of permanent magnets, which are essential for electric motors, wind turbine generators, etc.
- **Nickel:** Deposits located in Pará (PA), Goiás (GO) and Bahia (BA); contained nickel in total resource ~12.77 Mt (in producing areas, the contained nickel is ~3.66 Mt); widely used in the production of stainless steels, chemicals and aircraft turbines, and in shipbuilding, food processing and other applications.
- **Niobium:** World leadership (Araxá/MG, Catalão/GO); resource containing ~3.17 Mt of Nb2O5 equivalent (≈3.5 Mt FeNb or ≈2,22 Mt Nb); value chain has already advanced to high-purity alloys and oxides.
- **Copper:** Iron Oxide Copper Gold (IOCG) deposits located in Carajás and porphyry deposits in GO; potential supply in production ~32.54 Mt (total including research ~35.73 Mt); opportunity to advance in smelting/refining.

- **Iron Ore:** Main production areas are Carajás/PA and the Iron Quadrangle/MG; ~21,220 Mt Fe contained in resource in production; innovation in high-quality briquettes and pellets for low-carbon routes in the steel industry (direct reduction -DRI and electric arc furnaces - EAF).
- **Cobalt:** Nickel byproduct (GO, Piauí-PI, Minas Gerais-MG); ~110 kt contained cobalt in total resource (production + research); important for high-tech applications.
- **Bauxite/Aluminum:** Large deposits in Pará (PA) and Minas Gerais/Goiás (MG/GO); production potential from total resources ~898 Mt of alumina and ~475 Mt of aluminum; Brazil is a leader in can recycling (100% in 2022).

Demand for minerals in Brazil's path toward climate neutrality

Between 2025 and 2050, mineral demand in Brazil will be driven by technologies essential to the energy transition, including the expansion of crystalline silicon-based solar power, the advancement of modern wind turbines, the widespread adoption of batteries and electric motors, the development of fuel cells, and the completion of the Angra 3 nuclear power plant.

These technologies will drive demand for minerals such as copper, silicon, lithium, nickel, cobalt, graphite, manganese, tellurium and neodymium, particularly after 2035, when Brazil will need to accelerate the adoption of low-carbon solutions in order to meet its climate neutrality targets. Results from the analysis show significant leaps in projected demand between 2025 and subsequent decades for minerals such as lithium, graphite, copper and nickel. For example, the demand for lithium and nickel grows from 1 kt in 2025 to 43 kt and 35 kt, respectively, by 2050, while copper demand rises from 8 kt to 273 kt tonnes.

Anticipating this shift is crucial for Brazil to align its mineral base with emerging industrial demands and enhance its competitiveness in global value chains.

Key aspects of the comparative analysis of supply and demand for critical and strategic minerals in Brazil

Our combined analysis of supply and demand for critical and strategic minerals indicates that Brazil has significant geological potential and opportunities to integrate mineral and industrial policies.

Brazilian reserves of copper, graphite, lithium, nickel and cobalt significantly exceed the projected demand through 2050, with a notable surplus in nickel, which is 128 times the cumulative demand, and in copper and graphite, which are 19 and 43 times the projected demand, respectively.

However, domestic production remains limited and concentrated in the early stages of the chain. Realizing this production potential will enable Brazil to secure its domestic supply in strategic industries and position itself as a key global player capable of quenching the growing thirst for minerals, which the International Energy Agency expects to quadruple by 2040.

Investment and cooperation opportunities

There are strategic windows for Brazil to reposition itself in global chains:

- **Graphite:** develop capabilities in purification, spheroidization and coating for the production of anode material, anchored in hubs in Bahia, Minas Gerais and Ceará. Adopt traceability and low-carbon standards to access exacting markets.
- **Copper:** expand capabilities in smelting, refining and semi-finished products (cathodes, wires, sheets), integrating recycling and green metallurgy. Promote regional cooperation with Chile and Peru.
- **Lithium:** develop domestic processing of spodumene into battery-grade carbonate and hydroxide (Vale do Lítio/MG and new frontiers in the Northeast). Encourage battery recycling and sustainable hydrometallurgical routes.
- **Nickel:** increase production of class I nickel and sulfate, prioritizing hydrometallurgical routes (HPAL) when feasible, with clusters integrated with clean energy and competitive logistics. Promote recycling as a secondary supply source.
- **REE:** expand and strengthen separation and refining capabilities and the production of magnets (Araxá, Catalão). Encourage R&D in recycling and technology substitutes.
- **Iron:** prioritize high-value-added products (DRI pellets, briquettes) and decarbonize steelmaking with DRI/EAF routes and improved energy efficiency. Expand circularity and sustainable regional clusters.

Public policy recommendations

To maximize the extraction and utilization of its critical and strategic mineral resources, Brazil must establish policies that integrate mining, innovation and sustainability:

I. **A national CSM agenda:** modernize the regulatory framework with a focus on coordination across all government levels, efficient licensing, legal certainty, and alignment with existing policies such as the National Energy Transition Policy (PNTE), the Ecological Transformation Plan (PTE), the New Industry Brazil policy (NIB), and the Ten-Year Plan for Basic Geological Mapping and Mineral Resource Survey (Plan-GEO) as State policies.

II. **Green finance and instruments:** expand long-term credit and funding lines (FINEP-BNDES initiatives, Ecological Transformation Plan initiatives, and BNDES investment funds[3]), recognizing sustainable mining as an enabler of the transition.

III. **R&D and training:** provide technical training in the battery chain, REE, refining, and recycling; create pilot plants and foster partnerships between businesses, universities and research entities.

IV. **Enable infrastructure and clusters:** create an integrated infrastructure comprising railroads/ports and industrial parks located near deposits (Minas Gerais, Goiás, Pará, Bahia, Ceará) to stimulate midstream/downstream activities.

V. **Regional integration and offtakes:** establish agreements with neighboring countries and global buyers to responsibly diversify supply chains, ensuring traceability and demand predictability.

VI. **Upgrade Brazil's geological knowledge:** support PlanGeo 2025-2034, improving detailed mapping scales and reducing regional disparities to strengthen geoscientific knowledge, guide investments, and integrate remote sensing and geoinformation technologies into mineral and environmental planning.

VII. **Promote sustainable mining:** with stringent environmental, social and governance (ESG) standards capable of minimizing negative impacts, optimizing potentialities, and guaranteeing the economic and social well-being of the population.

3. See the "Financiamento Climático e Mineração" report (IBRAM, 2025b).

VIII. **Alignment between mineral supply and industrial demand:** construct planning mechanisms that connect Brazil's geological potential to the needs of emerging industrial chains (batteries, hydrogen, electrification).

IX. **Create strategic roadmaps for critical and strategic minerals:** facilitate the identification of chains with the highest competitive and technological potential, promoting coordination between R&D, industrial, and financing policies.

X. **Stimulate the circular economy in mining:** promote nationwide recycling programs for critical minerals, supporting pilot projects in urban mining and the reclamation of degraded areas.

Conclusion

Brazil boasts a robust mineral endowment and strong extraction chains, with recent advancements in low-carbon technologies, such as iron ore briquettes and cleaner refining routes. However, what separates potential from leadership is the ability to transform reserves into industrial and technological value, building a comprehensive and sustainable production chain that encompasses beneficiation, processing, manufacturing and recycling. This transition requires coordination between government, the private sector and academia, coupled with R&D policies, green financing, and low-carbon infrastructure, capable of transforming geological potential into strategic influence. This approach is aligned with Mission 3 of the New Industry Brazil policy (NIB), which, among other objectives, seeks to promote sustainable mobility to foster productive integration and well-being in cities - including challenges such as adding value to Brazil's mineral resources.

With regulatory predictability, innovation, and integration into higher value-added global supply chains, Brazil can evolve from a commodity exporter to a key player in the mineral midstream and downstream sectors, contributing to supply security, green reindustrialization, and the transition to a low-carbon economy. Brazil's emergence as a global CSM supplier will hinge on its ability to integrate into global supply chains, starting with the stages where Brazil can be most competitive. This requires integrating mineral exploration, technological innovation, and clean-technology manufacturing to realize Brazil's potential and ensure predictability of demand and of value chain integration opportunities.

1.

Introduction

Addressing the climate crisis requires a global effort to limit the average global temperature increase to below 2°C above pre-industrial levels, aiming to keep it below 1.5°C, as established in the Paris Agreement. Countries have set emission reduction targets whose achievement requires expanding the use of low-carbon technologies for renewable power generation, carbon capture and storage, improving energy efficiency, and electrifying energy-intensive sectors.

Although renewable energy technologies have a lower energy density than fossil fuels, they are more material-intensive. The increasing electrification of economies and the global adoption of clean technologies have, consequently, driven demand for minerals such as copper, lithium, cobalt, nickel and rare earth elements, which are essential inputs for wind turbines, photovoltaic panels, batteries and electric vehicle engines. According to the EPE (2025), a land-based wind farm requires nine times more mineral resources than a gas-fired power plant, and an electric car uses six times more mineral inputs than a conventional one. The International Energy Agency (IEA, 2025) also points out that, in the last two years, energy-related technologies have accounted for 65%-90% of the total growth in demand for metals such as cobalt, graphite, lithium, manganese and nickel. The IEA expects the demand for nickel to double by 2050 for use in electric vehicle (EV) engines. Moreover, since 2010, the average amount of minerals required for each new unit of energy generation capacity has increased by about 50%, which shows the growing dependence of the energy transition on these resources[4].

Given this scenario, the relationship between energy, low-carbon technologies, and minerals is becoming increasingly strategic. The reorganization of supply chains and the new geopolitical dynamics associated with the availability of these resources underscore the importance of understanding the role that

4. EPE. (2025). Minerais críticos e estratégicos para a transição energética. Retrieved from: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-877/Caderno_Minerais_Final.pdf#search=cadernos%20minerais

resource-rich countries - such as Brazil - can play in this context. Understanding Brazil's CSM potential requires exploring the global CSM landscape in the context of the energy transition, examining the challenges and opportunities associated with the reorganization of supply chains and associated geopolitical dynamics, and evaluating Brazil's position in this market. This chapter will briefly address those issues.

1.1. Theoretical framework of the study

The key to deeming a certain material critical or strategic primarily lies in the economic importance of the mineral and the associated supply risk. The imbalance between supply and demand for a certain mineral, shaped by technological, economic and geopolitical dynamics in specific contexts, establishes the basis for this classification. As supply chains reshape, the perception of which materials are considered critical may also change.

In general, minerals are deemed critical based on their importance to strategic supply chains and the constraints on their availability. These constraints are often driven by factors such as the geographic concentration of reserves, market dominance by a few suppliers, geopolitical instability, extreme weather events, environmental accidents, geological limitations, pandemics and armed conflicts. Minerals are considered strategic when a country has reserves that serves sectors with high domestic or global demand, due to their economic and geopolitical significance.[5]

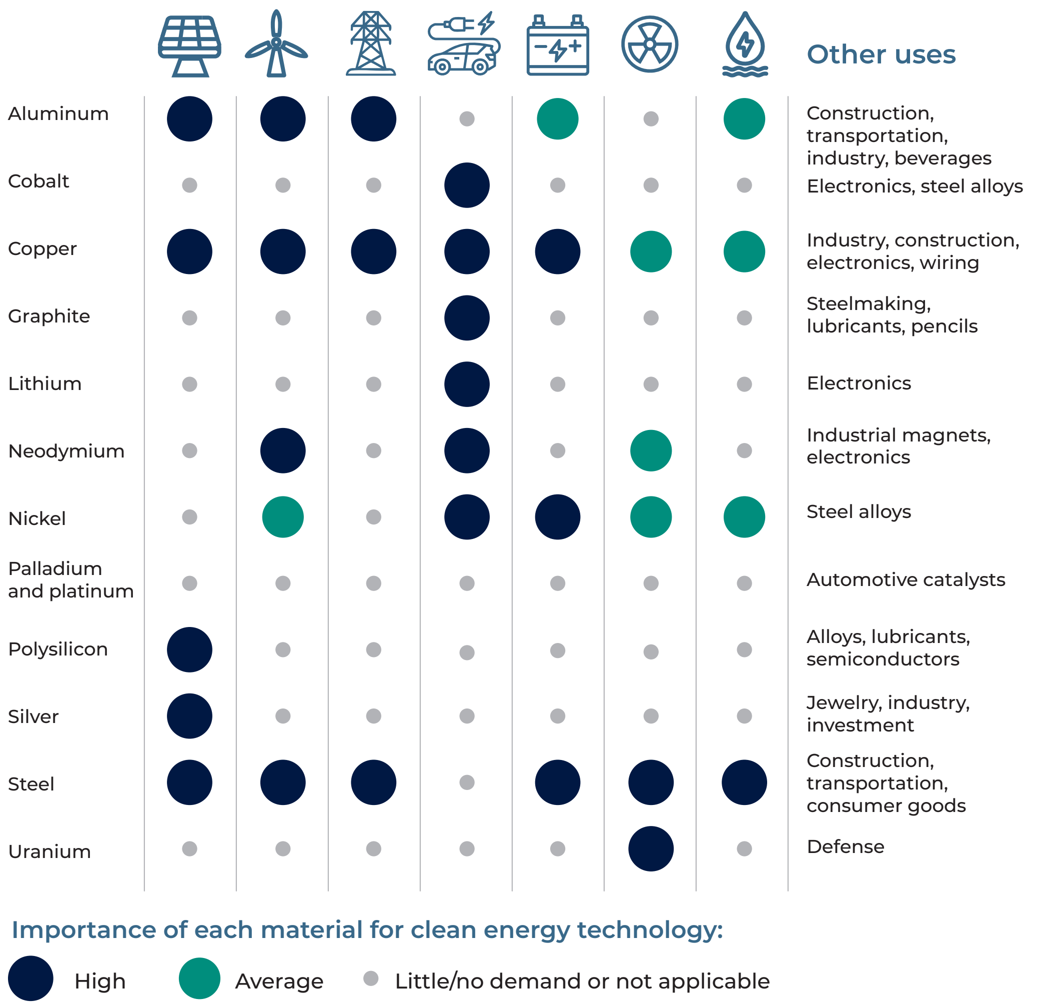
Different countries tend to assess criticality differently reflecting their unique perceptions of supply risks and demand shifts for these resources - the latter driven by factors such as economic growth, technological innovations, and regulatory changes. At the domestic level, each country or economic bloc defines CSM differently, based on its specific context. To give but a few examples, the United States Geological Survey published a list of 50 critical minerals in 2022 and recently added another 10 to the list. The European Union's (EU) Critical Raw Materials Act (CRMA) lists 34 critical "raw materials". This directly affects each nation's incentive policies and regulatory framework for a certain mineral.

The increasing reliance on minerals translates into risks of supply chain disruptions and price volatility. Beyond the pursuit of supply source diversification, this reliance also drives the search for alternatives, including recycling or substitution.

5. See IBRAM, 2025

Figure 1 provides a more detailed view of the demand levels for various minerals critical for the energy transition.

Figure 1. Impact level of demand for transition technologies on critical minerals



Note: Structural steel and aluminum for electric vehicles are not included in the energy transition demand because their use for that purpose does not represent "additional" demand, as these materials would be used in similar quantities in internal combustion engine vehicles. Source: ETC, 2023[6].

In Brazil, EPE defines a critical mineral as a resource essential to the economy, whose supply is at risk and whose absence could cause serious economic,

6. Retrieved from: https://www.tatasustainability.com/pdfs/Resources/_ETC_Report.pdf

environmental, security, and social impacts.[7] However, Brazil currently has no list of critical minerals, only of strategic materials.

Ministry of Mines and Energy (MME) Resolution no. 2, of 2021, sets out three criteria for a mineral to be deemed strategic.[8] This list covers a wide range of elements, distributed into three categories as detailed in the table below.

Table 1. Brazil's list of strategic minerals, according to the criteria set out in article 2 of Decree 10,657/2021

I - Minerals for which Brazil relies heavily on imports to supply vital sectors of the economy	
1. Sulfur	3. Potassium Ore
2. Phosphate Ore	4. Molybdenum Ore
II - Important minerals due to their application in high-tech products and processes	
1. Cobalt Ore	9. Silicon Ore
2. Copper Ore	10. Thallium Ore
3. Tin Ore	11. Tantalum Ore
4. Graphite Ore	12. Rare Earth Ore
5. Platinum Group Ores	13. Titanium Ore
6. Lithium Ore	14. Tungsten Ore
7. Niobium Ore	15. Uranium Ore
8. Nickel Ore	16. Vanadium Ore
III - Minerals that hold comparative advantages and are essential to the economy because of their contribution to Brazil's trade surplus	
1. Aluminum Ore	5. Gold Ore
2. Copper Ore	6. Manganese Ore
3. Iron Ore	7. Niobium Ore
4. Graphite Ore	8. Uranium Ore

Each research institution defined its own analytical framework based on the Brazilian list of strategic minerals, and according to specific methodologies and approaches. As mentioned earlier, CETEM and SGB considered the resources in terms of mineral endowment and reserves whose extraction is technically and economically feasible, as well as mineral products associated with the

7. EPE. (2025). Minerais críticos e estratégicos para a transição energética. Retrieved from: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-877/Caderno_Minerais_Final.pdf

8. Retrieved from: https://www.gov.br/mme/pt-br/assuntos/noticias/mme-lanca-relatorio-anual-do-comite-interministerial-de-analise-de-projetos-de-minerais-estrategicos/resolucao2CTAPME.pdf.

midstream, downstream and secondary material recovery stages. Conversely, the Cenergia (Coppe/UFRJ) structured its analysis around the mineral demand associated with energy converters. The methodology and material intensity driving this analysis are detailed in Appendices A and B. It follows that the lists of minerals whose supply and demand were examined vary, reflecting each institution's approach.

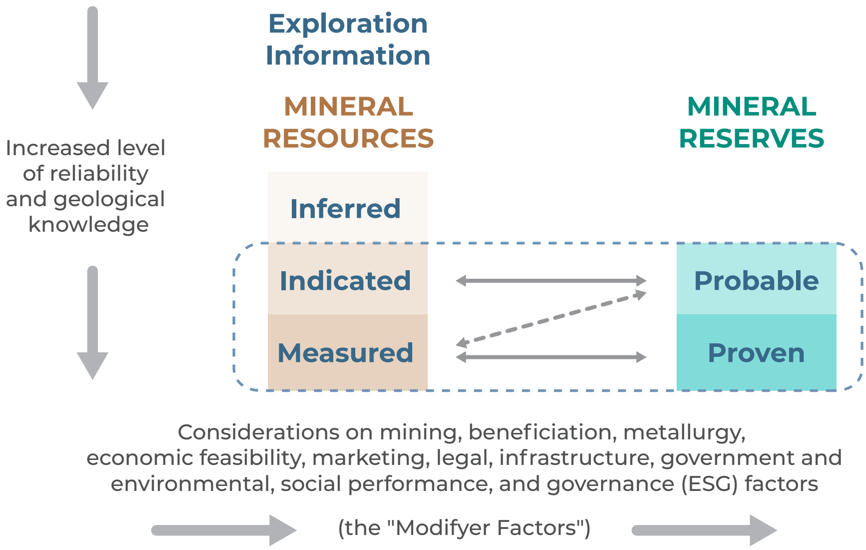
Another significant differentiation occurs in relation to the concepts of mineral endowment, resource and reserve, which refer to distinct stages of geological knowledge. The mineral reserve represents the first stage in defining supply, while mineral endowment refers to the quantity and diversity of available mineral resources. Reserves are those resources that can be extracted according to technical, economic and legal requirements.

Table 2. Theoretical framework for mineral endowment, resource and reserve

Mineral endowment	The entire range of minerals in a given geographic area, whether known or unknown. It is the total geological potential, encompassing both identified resources and minerals yet to be discovered.
Resource	The known portion of a mineral endowment. Minerals whose existence has been confirmed through geological studies, including both those with proven economic viability and those whose extraction is not as yet feasible.
Reserve	The portion of the resources that can be economically extracted. In other words, this is the portion whose extraction is feasible from an economic, technical and technological standpoint.

Resources can be further divided into inferred, indicated or measured, while reserves can be considered probable or proven. This connects with the reliability level of geological knowledge (see figure 2).

Figure 2. Parameters for the classification of mineral resources



Source: CBRR, 2022[9]

Finally, defining upstream, midstream and downstream in mining is key for the purposes of this report, as these are the three main stages in the extractive and energy industry value chains. "Upstream" corresponds to the initial activities focused on the exploration and production of natural resources, such as geological prospecting, extraction, and primary beneficiation of minerals. "Midstream" involves logistics and intermediate processing, including transportation, storage and partial refining of inputs, connecting production points to processing or consumption units. "Downstream" refers to the final stages of the chain, encompassing refining, manufacturing, distribution and marketing of final energy products, metals and byproducts. Collectively, these three segments cover the full path from the resource's origin to its industrial use or final consumption.

1.2. Overview of mineral supply and consumption

The definition of what a critical and strategic mineral is underscores the importance of addressing the distribution of these minerals and the major trends of their global flows.

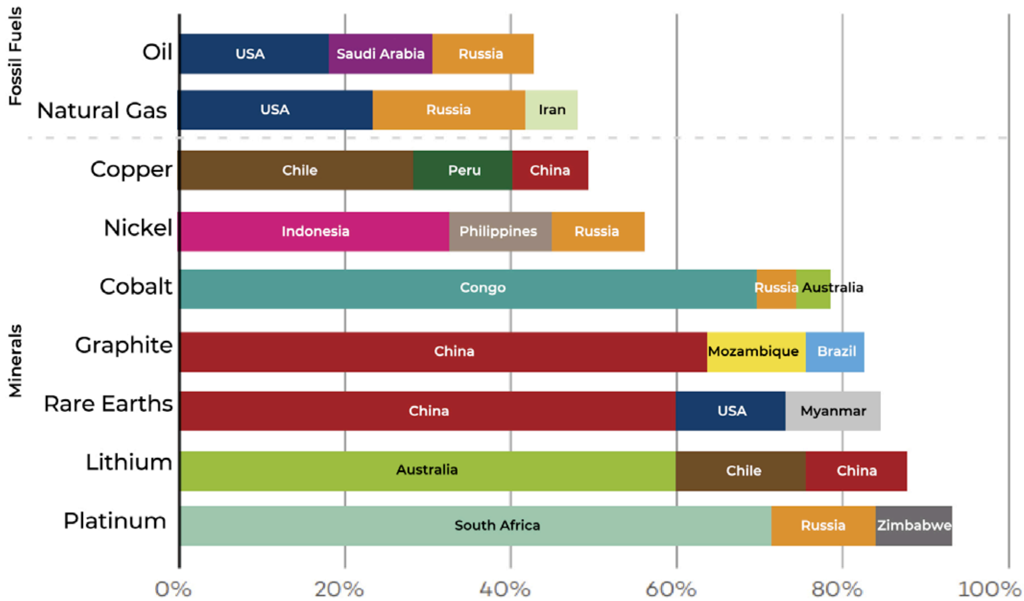
In terms of supply, Asia stands as the largest mining region in the world, having extracted approximately 10 billion tonnes in 2017. Data from the IEA (2025) show

9. Brazilian Commission on Resources and Reserves - CBRR. 2022 CBRR Form for reporting exploration results, resources and mineral reserves.

that critical mineral production and refining in Asia is concentrated in China. In extraction and production, China holds a global share of 22% of lithium, 61% of rare earth elements (REEs), and 87% of graphite. In refining, its global share reaches 44% of copper, 70%-75% of lithium and cobalt processing, and 90% of REE and graphite refining for batteries.[10]

Oceania, particularly Australia, and Latin America, particularly Chile, contribute nearly equally to the supply of global minerals. Africa accounts for approximately 30% of the world's critical mineral reserves, but its global participation is hindered by limitations in transportation infrastructure, geological studies, and processing and refining capabilities for critical minerals.[11] This challenge, which some Latin American countries also face, has led these nations to focus their investments primarily on the upstream segment of the extractive industry. Canada, the United States (USA) and Europe also account for a significant share of global mineral production, albeit with lower annual growth rates when compared to other regions.

Figure 3. Participation of the three main producing countries in the total production of minerals and oil and natural gas, 2019



Source: Adapted from IEA (2021)[12]

10. IEA. (2025). Global Critical Minerals Outlook 2025. Retrieved from: https://www.iea.org/reports/global-critical-minerals-outlook-2025

11. IMF. (2024). Digging for Opportunity: Harnessing Sub-Saharan Africa's Wealth in Critical Minerals. Retrieved from: https://www.imf.org/-/media/Files/Publications/REO/AFR/2024/April/English/MineralsNote.ashx

12. World Energy Outlook 2021. Retrieved from: https://www.iea.org/reports/world-energy-outlook-2021

The figure above shows the geographic concentration of critical minerals. According to UNECE (2024), more than 75% of these resources are located in Australia, China, Chile and the Democratic Republic of Congo (DRC). This geographic concentration is accompanied by an increase in global supply. According to the IEA (2025), the growth rate in the supply of battery minerals since 2020 has been double that observed in the late 2010s. In 2024, approximately 90% of that growth was driven by a single major supplier: Indonesia for nickel, and China for cobalt, graphite and rare earths.

Data from the IEA also show that the growth in supply, primarily led by China, Indonesia and some African states, has outpaced demand. This trend adds to the economic uncertainties and market fluctuations that impact investments in the sector. Investment in the development of critical minerals lost steam in 2024, growing by only 5%, compared to 14% in 2023. When adjusted for cost inflation, real growth was only 2%. These factors have put downward pressure on the prices of certain minerals, particularly cobalt, graphite, lithium, nickel and manganese.

As for demand, China is the largest importer of critical minerals. According to the IEA (2025), China is seeking to secure access to these resources through direct investments in overseas mines, channeled through state-owned companies with political backing from the government. In 2024, the mining sector was the second-largest recipient of Chinese financing under the Belt and Road Initiative, accounting for 18% of the total - approximately USD 21.4 billion. China is heavily dependent on the DRC for the supply of materials for its cobalt refineries. Thomas (2023) points out that the DRC exports more than 80% of its cobalt to China.

Other than China, the USA, Europe and Japan also are major consumers. The IEA (2025) reported that in 2024 lithium demand grew by 30%, while demand for nickel, cobalt, copper, graphite and REEs increased by 3%-8%. According to this same source, energy sector technologies contributed 65%-90% of total growth in mineral demand in the last two years.

In addition to the dynamics of supply and demand, other factors such as political stability, the efficiency of licensing processes, and energy security directly impact the market conditions for minerals. For the purposes of this report, a comparative analysis was conducted on the regulatory frameworks, policies, and key challenges to mineral production across 16 countries with significant mineral output[13]. The main barriers to production identified include: poor coordination between the federal government and subnational

13. The countries analyzed were: Australia, Argentina, Brazil, Canada, Chile, China, USA, Philippines, Guinea, India, Indonesia, Madagascar, Myanmar, Peru, DRC and Russia.

entities; regulatory complexity or fragility; and social and political instability. These barriers are described in further detail in chapter 5 of this report.

These structural challenges, combined with the geographical concentration of critical minerals, have driven a series of international developments. US and European strategies focus on the diversification of partners and sources of supply. This was evident at the 2025 G7 Leaders' Summit[14], where member countries endorsed the Action Plan for Critical Minerals, committing to the responsible and sustainable diversification of mineral supply chains. This commitment in the European Union is aligned with the Critical Raw Materials Act, which stipulates that dependence on a single non-EU country for any critical raw material must not exceed 65% of its consumption.[15]

As for Asia, Steinhaeuser (2025) notes that the New Silk Road may serve as a tool for China to enhance its involvement in global mineral supply chains. In Latin America, there is a growing debate on China's increasing influence and the need for greater regional coordination on resource governance. In Oceania, the ban on deep-sea mining emerges as a new frontier of dispute over the limits of mineral extraction. Finally, in Africa, alongside policies of mineral nationalism, South Africa leveraged its G20 presidency[16] to position critical and strategic minerals as a central pillar of its agenda, aiming to launch the G20 Critical Minerals Framework with the goal of ensuring that these resources serve as catalysts for sustainable development.

The concentration of mineral reserves and processing and refining capabilities in a few countries - coupled with an interdependent international trade system and growing demand for these materials - can make supply chains vulnerable to geopolitical risks, triggering international disputes. Brazil's context and potential must be examined against this backdrop.

1.3. Brazil's position on CSM

The mining sector plays a strategic role in Brazil's economy, accounting for a significant share of exports. In 2024, the Brazilian mining sector reported a revenue of R$ 270.8 billion and a trade surplus of USD 34.9 billion, accounting

14. The G7 brings together the world's leading industrialized economies - Germany, Canada, the United States, France, Italy, Japan and the United Kingdom - to coordinate economic policies and discuss global issues.

15. European Parliament. (2023). Critical Raw Materials Act. Retrieved from: https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/747898/EPRS_BRI(2023)747898_EN.pdf

16. The G20 is a forum comprising 19 countries, the African Union and the European Union, representing the majority of global GDP and focusing on economic cooperation and sustainable development.

for 47% of the nation's trade surplus[17]. According to a report by IPEA and MME, the mineral production chain contributed between 2.5% and 4% of Brazil's GDP in recent decades. Around 90% of this contribution comes from iron ore extraction. The remainder is split between approximately 5% from non-metallic minerals (such as limestone, clay, and others primarily used in cement and ceramics production), and 5% from non-ferrous metallic minerals, including critical and strategic minerals.

This production is mostly exported. According to IBGE (2021), exports from the mineral extraction industry account for about 65% of total demand. The remaining 35% were taken by domestic demand. As the leading product, iron ore exports accounted for approximately 75% of total demand. Domestic demand predominates for non-metallic minerals (at 94% of the total), primarily for use in the construction industry. Non-ferrous metals show a relative balance between exports and domestic demand, with approximately half of total demand absorbed domestically and the other half exported.

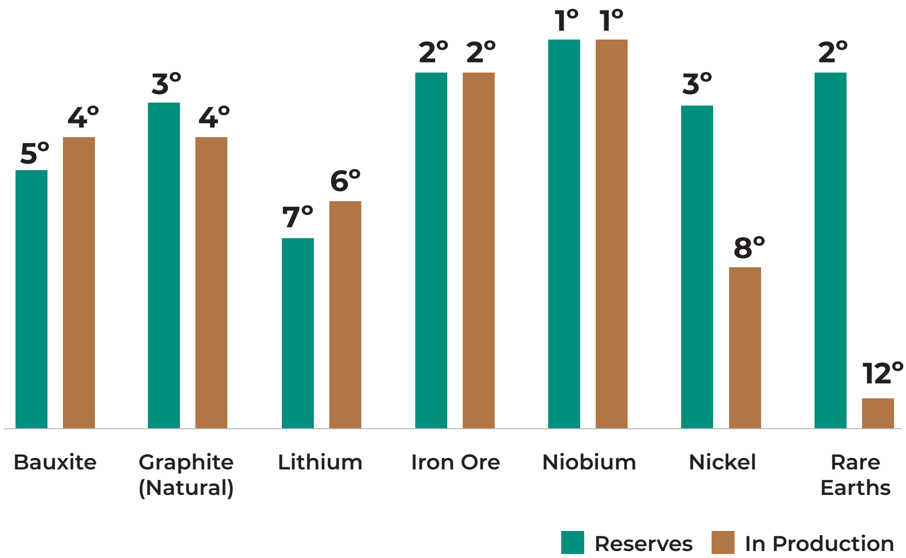
Although CSM represent a relatively limited share of total output, their existing reserves and high growth potential give them a crucial role in the future of the mineral extraction industry, as this report will discuss.

Brazil's extensive territory and diverse geology have given it a vast mineral endowment, including natural reserves of iron, gold, copper, nickel, aluminum and niobium, among others. Fifteen of these minerals account for 99% of the value generated by metallic minerals: aluminum, lead, copper, columbite-tantalite, chromium, tin, graphite, iron, lithium, manganese, niobium, nickel, gold, vanadium and zinc.

Brazil is a world leader in several of these resources. The figure below shows Brazil's global standing in reserves and production volumes for the minerals whose supply was analyzed.

17. IBRAM. (2025). Setor mineral | 2024. Retrieved from: https://ibram.org.br/wp-content/uploads/2025/02/DADOS_Setor-Mineral_2024_5FEV2025.pdf

Figure 4. Brazil's global standing in reserves and production volumes for the minerals analyzed



Data source: USGS, 2025[18].

Brazil's Southeast and Center-West regions concentrate a significant portion of mineral production, primarily iron, graphite, nickel and niobium, as well as the nation's only operational REE project. This concentration reflects both the favorable geology and the high level of logistical and industrial maturity in these areas. In the Southeast region, the Iron Quadrangle and the "carbonate district" of Araxá (MG) stand out, while the Center-West, especially northern Goiás, is noted for its nickel, bauxite and REE operations. The Jequitinhonha Valley (MG) emerges as a new strategic hub, driven by the expansion of lithium operations.

Elsewhere in Brazil, the North hosts large-scale operations integrated with export corridors, such as Carajás and Porto Trombetas (PA), focused on the production of iron, copper and bauxite. The Northeast is home to active projects in nickel, copper, iron and lithium, as well as an operation that yields cobalt as a byproduct, and natural graphite mines in Bahia. This territorial distribution reflects Brazil's geological diversity and boosts its potential to integrate into global value chains and levrage its strategic mineral resources in support of the energy transition, technological innovation, and sustainable development.

Although the reserves identified are diverse and substantial in volume, the production process for the majority of minerals remains concentrated in the

18. USGS Mineral Commodity Summary 2025 - https://pubs.usgs.gov/periodicals/mcs2025/mcs2025.pdf

upstream and midstream stages, with only a limited number advancing to the downstream segment of the value chain.

The export of commodities and the import of finished goods is the prevalent pattern for most of the mineral products analyzed. This represents the main current challenge in unlocking Brazil's potential in the mineral sector.

Other challenges, such as gaps in geological mapping, high operating costs stemming from the so-called “Brazil Cost”, regulatory hurdles, and social and environmental conflicts, sap competitiveness and the attraction of investments. That said, recent initiatives in regulatory modernization, economic incentives, and upgraded state governance represent promising opportunities for progress. Some of these bottlenecks and opportunities will be addressed in further detail in Chapters 5 and 6.

Brazil's current position in the international mineral trade shows a diversified geographic distribution, particularly focusing on emerging countries and industrialized economies that play a strategic role in global supply chains. This configuration underscores both Brazil's alignment with the demands of major consumer hubs in Asia and Europe, and the potential for strengthening South-South partnerships in the mineral sector. Brazil's key export partners include Germany, Argentina, Canada, China, South Korea, the United States, Japan, Malaysia, the Netherlands, and Switzerland. At the subnational level, the states with the highest export values in 2024 were Bahia, Ceará, Espírito Santo, Goiás, Maranhão, Mato Grosso, Minas Gerais, Pará, Rio de Janeiro, and São Paulo.[19]

Key import partners include South Africa, Germany, Argentina, Chile, China, the United States, India, Mexico, Peru and Russia.[20] Despite its comparative advantages in minerals such as niobium and iron, Brazil remains heavily reliant on the import of certain minerals for vital sectors, such as agrominerals for fertilizers. This vulnerability became clear in 2022, when the Russia-Ukraine conflict threatened the global supply chain - a significant impact for Brazil, which imported approximately 85% of its fertilizers and relied on Russia for 23%.[21]

In summary, Brazil holds a strategic position in the CSM landscape, combining vast geological potential with increasing international focus on supply chain diversification and the energy transition.

19. Export data obtained from Comex Stat (2024)

20. Import data obtained from Comex Stat (2024)

21. G1. (2022). Guerra na Ucrânia: por que o Brasil depende tanto dos fertilizantes da Rússia? Retrieved from: https://g1.globo.com/economia/agronegocios/noticia/2022/03/03/guerra-na-ucrania-por-que-o-brasil-depende-tanto-dos-fertilizantes-da-russia.ghtml

However, to fully harness this potential, Brazil must overcome structural challenges and develop a national strategy that integrates economic competitiveness, sustainability and social inclusion. The subsequent chapters aim to offer strategic insights on this topic by analyzing the supply and demand for critical and strategic minerals, identifying bottlenecks, and proposing concrete steps for Brazil to progress in this sector.

2.

Brazil's supply potential

This report provides a detailed analysis of the supply of lithium, graphite, REEs, nickel, niobium, copper, iron ore, cobalt and bauxite, using them as examples of critical and strategic minerals essential for the energy transition. The comprehensive analysis of the nation's endowment of these resources shows that Brazil holds substantial reserves and can potentially play a significant role in the global energy transition. Brazil's output of these minerals can expand in the coming years through the addition of new resources, reserves or production inputs. The evaluation of mineral supply in this report was based on resources in the form of mineral endowment, reserves (derived from resources whose extraction is technically and economically feasible), and the mineral output in the midstream, downstream and secondary material recovery stages.

The sections below present the main production characteristics of each selected mineral, covering mineral endowment, key projects, value chain, and an estimate of the ore grade of the resource. The opportunities for the development of priority mineral supply chains are described in Chapter 6 of this report.

2.1. Graphite

Graphite is a crystalline form of carbon with a hexagonal structure. Its main characteristics include high stability, excellent electrical and thermal conductivity, chemical and thermal resistance, low density, and high structural stability. It is widely used in various industrial sectors as electrodes in electric arc furnaces for steel production; refractories in high-temperature furnaces for steelmaking, casting, and cement production; mechanical components such as seals, bearings and electric motor brushes; and as a reinforcing agent in the composition of plastics and rubbers. Graphite plays a central role in the energy transition, particularly in energy storage technologies

Brazil's Graphite Mineral Endowment

Brazil produced 66,300 tonnes of graphite concentrate in 2023 and 68,000 tonnes in 2024, showing a 2.6% expansion. Given its significant potential, graphite production in Brazil has considerable room for growth, with investments in the sector expected to increase in the coming years.

The Bahia-Minas Province is one of the leading graphite producers in the world. Located in southern Bahia, the Santa Cruz mine began production in 2024 with a capacity of 12,000 tonnes of graphite concentrate per year, with potential for expansion to 50,000 tonnes per year in subsequent phases. Other regions, such as the Central Ceará Graphite Province, the Amazon Craton, the Araguaia Belt, the Paraguay Belt, and the Brasília Belt, have yet untapped potential for graphite production (SGB-CPRM, 2025).

The main graphite reserves are located in the states of Minas Gerais, Bahia and Ceará. Thanks to growing demand and Brazil's standing as the world's fourth-largest graphite producer, Brazil offers attractive long-term prospects for graphite exploration.

In Brazil, graphite is primarily found in metamorphic environments[22], such as Proterozoic Orogenic Belts. The degree of crystallization and the quality of the ore are influenced by metamorphism, as well as temperature and pressure conditions.

Main Projects and Companies in Brazil

Brazil's major deposits are shown on the map and listed in the table below:

22. Metamorphic environments are geological settings where preexisting rocks undergo physical and chemical transformations due to high temperatures, pressures, and/or the presence of active chemical fluids.

Figure 5. Map showing the location of major graphite deposits

Table 3. Brazil's major graphite deposits

DEPOSIT	COMPANY	RESOURCES	GRADE (TGC)	STATUS
Mina Itapecerica	Nacional de Grafite Ltda.	209.59 Mt	9.79%	In Production
Mina Mateus Leme	Grafita MG Ltda.	91.67 Mt	14%	In Production
Mina Maiquinique	Extrativa/Grafite do Brasil	33.3 Mt	9.6%	In Production
Mina Pedra Azul	Nacional de Grafite Ltda.	19.07 Mt	12.59%	In Production
Peresópolis	Lucra Minerals Ltda.	40 Mt	14%	In Research
Porto Nacional	Di Castro's Construtora Ltda.	49.7 Mt	5.3%	In Research
Mina de Salto da Divisa	Nacional de Grafite Ltda.	232.6 Mt	25%	In Production
Santa Cruz[1]	South Star Mining Corp.	14.9 Mt	2.29%	In Research
Santa Terezinha	Mineração de Calcário Montevidiu Ltda.	7.50 Mt	6.33%	In Research

CG = Graphite Concentrate. TGC = Total Graphitic Carbon. Source: 1 - South Star, 2020; SGB, 2025.

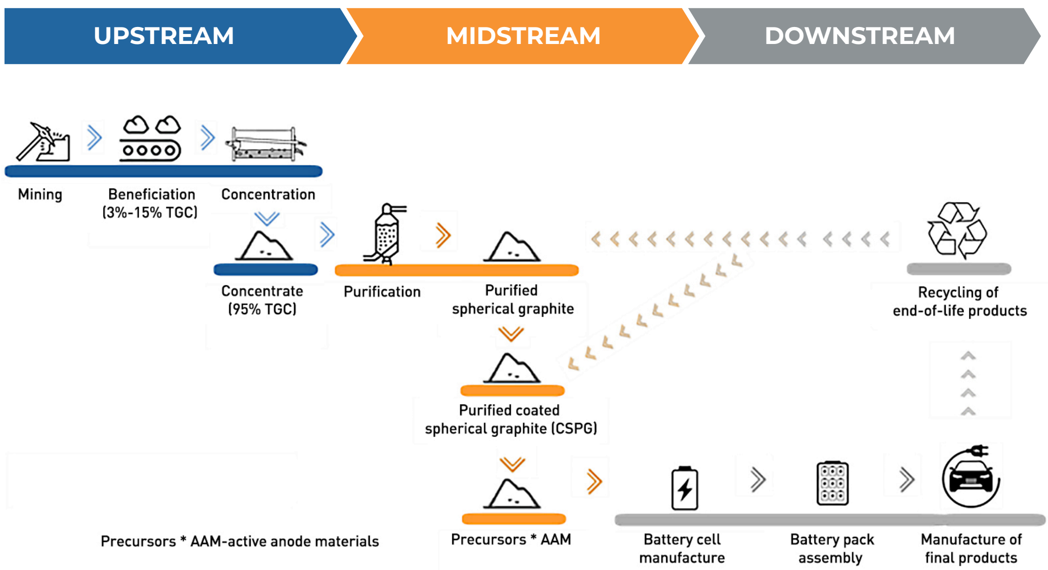
Value Chain

The natural graphite production chain, running from mining to lithium-ion battery production, consists of six main stages: mineral extraction, beneficiation, purification, spheroidization, surface coating, and the production of active anode material (AAM).

The extraction and processing stages make up the upstream sector of the chain focused on the battery industry. The extracted ore typically contains 3% to 15% total graphitic carbon (TGC). Conventional mineral beneficiation techniques such as crushing, grinding, gravity separation, and flotation will increase TGC levels to 80%-95%.

To meet the stringent standards required for battery anode applications, an additional purification process is necessary to raise the material's purity to at least 95% TGC. The purification, spheroidization and coating processes make up the midstream sector. The final product of these stages, coated spherical graphite, is directly used as the active material in battery anodes (active anode material - AAM).

Figure 6. Graphite value chain



Estimation of total graphitic carbon content in the resource

The total graphitic carbon content from the reported resources of producing deposits amounts to 97.10 Mt, with a further 8.25 Mt in research-stage deposits, for a combined total of 105.35 Mt.[23]

Table 4. Calculation of graphitic carbon content in the resource[24]

DEPOSIT	COMPANY	STATUS	RESOURCE (Mt)	GRADE (TGC)	TOTAL GRAPHITIC CARBON (Mt)
Itapecerica Mine	Nacional de Grafite Ltda.	In Production	209.59	9.79	20.52
Mateus Leme Mine	Grafita MG Ltda.	In Production	91.67	14.00	12.83
Maiquinique Mine	Extrativa/Grafite do Brasil	In Production	33.30	9.60	3.20
Pedra Azul Mine	Nacional de Grafite Ltda.	In Production	19.07	12.59	2.40
Salto da Divisa Mine	Nacional de Graphite Ltda.	In Production	232.60	25.00	58.15
Santa Cruz*	South Star Mining Corp.	In Research	14.90	2.29	0.34
Peresépolis	Lucra Minerals Ltda.	In Research	40.00	12.00	4.80
Porto Nacional	Di Castro's Construtora Lida.	In Research	49.70	5.30	2.63
Santa Terezinha	Mineragéo de Calcério Montevidiu Ltda.	In Research	7.50	6.33	0.47
São Benedito Mine	São Benedito	Interrupted	2.09	57.43	1.20
TOTAL					**105.35**

Recyclability

In general, graphite is not recovered in the recycling process of lithium-ion batteries, which typically focuses on the recovery of elements with higher economic value. But graphite can be recovered from both batteries and refractory materials, and the recovered material can be reused in applications such as brake pads and thermal insulation.

23. These calculations were based on total reported resources, excluding losses in the processing stages. For more information, see Appendix A — Methodology.

24. The calculation covered the research and production phases, excluding reserves that are presently inactive.

Replaceability

Natural graphite can be partially replaced by synthetic or alternative materials in various industrial applications. Synthetic graphite powder, discarded machined-shape residues, and calcined petroleum coke compete with one another as feedstocks in iron and steel production. Both synthetic graphite powder and secondary synthetic graphite derived from the machining of graphite blocks also compete for use in the battery sector.

Finely ground coke combined with olivine shows promise as a potential competitor for foundry molding applications. Molybdenum disulfide is a dry lubricant that competes with graphite, despite being more sensitive to oxidizing environments.

2.2. Lithium

Lithium (Li) is an alkali metal essential to the energy transition because of its key role in the production of rechargeable batteries for electric vehicles and energy storage systems. Its properties - low density, high electrochemical potential, and high reactivity - provide superior performance for clean energy technologies. Although lithium has traditionally been used in ceramics, glass, lubricants and pharmaceutical products, today approximately 87% of global demand is directed toward battery manufacturing, reflecting the rapid growth of electromobility and the digitalization of the economy (USGS, 2025).

Brazil's Lithium Mineral Endowment

Brazil has the potential to become a global player in lithium production in the coming years. Brazil produced 5,260 tonnes of contained lithium in 2023 and 10,000 tonnes last year, showing a 90% increase compared to 2023. With total estimated reserves of 1.37 million tonnes (MME, 2025), Brazil ranks seventh globally, holding 4.4% of the world's total. Brazil's resources are estimated at approximately 1.3 million tonnes (USGS, 2025).

In Brazil, lithium is primarily found in lithium-cesium-tantalum (LCT) pegmatite deposits. The main ore mineral is spodumene, followed by amblygonite, petalite and lepidolite (SGB, 2025).

Main Projects and Companies in Brazil

Brazil's major deposits are shown on the map and listed in the table below:

Figure 7. Map showing the location of major lithium deposits

Table 5. Brazil's major lithium deposits

DEPOSIT	COMPANY	RESOURCES	GRADE (Li_2O)	STATUS
Nezinho do Chicão - Lavra do Meio (NDC- LDM)[1]	Sigma Lithium Resources	38.4 Mt	1.41 %	In Research
Barreiro[1]	Sigma Lithium Resources	25.6 Mt	1.36 %	In Research
Projeto Bandeira[2]	Lithium Ionic Corp	23.68 Mt	1.34 %	In Research
Volta Grande/Nazareno[3]	AMG	20.29 Mt	1.06 %	In Production
Xuxa[1]	Sigma Lithium Resources	14.7 Mt	1.55 %	In Production
Murial[1]	Sigma Lithium Resources	14.6 Mt	1.28 %	Unexplored
Salinas - Baixa Grande[4]	Lithium Ionic Corp	6.52 Mt	1.11 %	Unexplored
Cachoeira Mine	Companhia Brasileira de Lítio	4.5 Mt	1.40 %	In Production

Itinga - Outro Lado[5]	Lithium Ionic Corp	2.97 Mt	1.46 %	Unexplored
Seridozinho - Mina Velha	Miranda Mineração Ltda	N/A	N/A	Intermittent production
Samambaia Mine	Sigma Lithium Resources	N/A	N/A	Closed/Exhausted
Tesoura Mine	Tesoura Mine	N/A	N/A	Closed/Exhausted

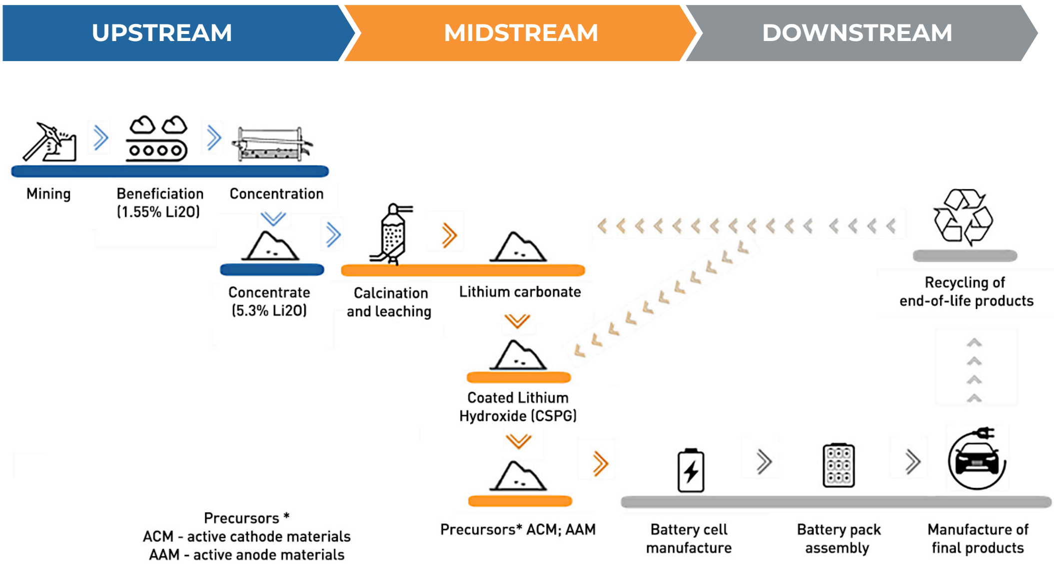
Sources: 1 - Sigma Lithium Resources, 2025; 2- Lithium Ionic, 2024a; 3- AMG, 2017; 4- Lithium Ionic, 2024b; 5- Lithium Ionic, 2023.

Value Chain

The starting point of the lithium value chain for lithium-ion batteries is the mining of lithium-bearing minerals, primarily spodumene. Although this mineral can contain up to 8% Li2O, its commercial concentrates typically range between 4% and 6%. The beneficiation process involves comminution, dense media separation, flotation and magnetic or gravity concentration, to produce concentrates that are then sent for calcination and acidic or alkaline leaching, converting lithium into soluble compounds such as sulfate, carbonate or chloride. The most common route in Brazil includes conversion to lithium sulfate (Li2SO4) using sulfuric acid, followed by purification and final precipitation.

Following purification, techniques such as ion-exchange, evaporation and crystallization are employed to produce high-purity compounds - carbonate (Li2CO3), chloride (LiCl) and hydroxide (LiOH) - which are used as precursors for cathode materials. Some of the main compounds used in batteries are lithium iron phosphate (LiFePO4), lithium manganese oxide (Li2MnO4) and lithium cobalt oxide (LiCoO2). Lithium processing and refining face high operating costs due to the intensive use of imported reagents, such as soda ash and sulfuric acid, and the chemical purity requirement for battery-grade lithium.

Figure 8. Lithium value chain



Estimation of lithium content in the resource

Table 6 shows the conversion factors for lithium compounds and minerals used to estimate the lithium content in the resource expressed as lithium carbonate equivalent (LCE). This standardized unit expresses the total amount of lithium in a deposit, theoretically converted to lithium carbonate, which enables direct comparisons across various reports and industry studies. The conversion to LCE assumes total recovery of the lithium content, disregarding losses during extraction and beneficiation processes. Lithium reserves and resources are therefore frequently reported in tonnes of LCE or metallic lithium (Li).

Table 6. Conversion factors between lithium compounds and minerals

ORIGIN	CONVERT TO LI	CONVERT TO LI_2O	CONVERT TO LI_2CO_3	CONVERT TO $LIOH.H_2O$
Metallic lithium (Li)	1.000	2.153	5.325	6.048
Lithium oxide (Li_2O)	0.464	1.000	2.473	2.809
Lithium carbonate (Li_2CO_3)	0.188	0.404	1.000	1.136
Lithium hydroxide monohydrate ($LiOH.H_2O$)	0.165	0.356	0.880	1.000
Lithium fluoride (LiF)	0.268	0.576	1.424	1.618

Table 7 presents the estimated lithium content in the resource, calculated using these equivalence factors, which is then used to estimate the potential production of lithium-ion batteries (Table 8), according to the average composition of each type of battery chemistry (Table 9). These calculations represent a theoretical maximum scenario in which all available lithium is allocated to battery production.

Table 7. Calculation of the estimated lithium content in the resource

DEPOSIT	COMPANY	STATUS	RESOURCES (Mt)	GRADE (Li_2O%)	CONCENTRATE - GRADE (Li_2O%)	EFFICIENCY OF THE CONCENTRATION PROCESS (%)	SPODUMENIUM CONCENTRATE 5.3% Li_2O (Mt)	Li2O (Mt)	LCE (Mt)	LiOH-H_2O (Mt)	Li (Mt)
Volta Grande	AMG	In Production	20.29	1.06	5.2	80	3.31	0.17	0.43	0.48	0.08
Xuxa	Sigma Lithium Resources	In Production	14.7	1.55	5.2	80	3.44	0.18	0.45	0.5	0.08
Cachoeira Mine	Companhia Brasileira de Lítio	In Production	4.5	1.4	5.2	80	0.97	0.05	0.12	0.13	0.02
Total in production			**39.49**	**1.34**	**5.2**	**80**	**7.72**	**0.4**	**1**	**1.13**	**0.19**
Nezinho do Chicão - Lavra do Meio (NDC - LDM)	Sigma Lithium Resources	In Research	38.4	1.41	5.2	80	8.33	0.43	1.07	1.21	0.2
Barreiro	Sigma Lithium Resources	In Research	25.6	1.36	5.2	80	5.36	0.27	0.67	0.76	0.13
Projeto Bandeira	Lithium Ionic Corp	In Research	23.68	1.34	5.2	80	4.88	0.24	0.6	0.69	0.11
Total in research			**87.68**	**1.37**	**5.2**	**80**	**18.57**	**0.97**	**2.39**	**2.69**	**0.44**
Murial	Sigma Lithium Resources	Unexplored	14.6	1.28	5.2	80	3.58	0.19	0.47	0.53	0.09
Salinas - Baixa Grande	Lithium Ionic Corp	Unexplored	6.52	1.11	5.2	80	1.11	0.06	0.15	0.17	0.03
Itinga - Outro Lado	Lithium Ionic Corp	Unexplored	2.97	1.46	5.2	80	0.67	0.03	0.09	0.1	0.02
TOTAL			**151.26**				**30.94**	**1.61**	**3.39**	**4.49**	**0.74**
USGS Data for Brazil's Reserve			**0.39**	**1.55**	**5.2**	**80**	**0.09**	**0**	**0.01**	**0.01**	**0**

Table 8. Calculation of potential kWh based on the total lithium content in the resource

CATHODE	LFP	LMO	LMNNO	NMC111	NMC532	NMC622	NMC811	NMC955	NCA	AVERAGE
Li (kg per kwh)	0.08	0.08	0.08	0.11	0.1	0.1	0.09	0.09	0.09	0.091
kwh for lithium supply (0.74 Mt)	9.27 x10	9.27 x10	9.27 x10	6.74 x10	7.42 x10	7.42 x10	8.24 x10	8.24 x10	8.24 x10	8.124 x10

Table 9. Calculation of the estimated lithium content in the resource

TECHNOLOGIES		LFP	LMO	LMNNO	NMC111	NMC532	NMC622	NMC811	NMC955	NCA
Cathode	Li	0.08	0.08	0.08	0.11	0.1	0.1	0.09	0.09	0.09
	Ni			0.34	0.32	0.45	0.52	0.61	0.82	0.66
	Mn		1.37	0.97	0.33	0.27	0.18	0.08	0.04	
	Co				0.32	0.18	0.17	0.08	0.04	0.13
	Fe	0.68								
	P	0.38								
Anode	Graphite	1	0.85	0.85	0.9	0.9	0.9	0.9	0.9	0.9
(0% Si)	Si									
Anode	Graphite	0.84	0.71	0.71	0.75	0.75	0.75	0.75	0.75	0.75
(2% Si)	Si	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Anode	Graphite	0.48	0.41	0.41	0.43	0.43	0.43	0.43	0.43	0.43
(10% Si)	Si	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Recyclability

Lithium is infinitely recyclable, and its recovery from lithium-ion batteries is increasing with the deployment of recycling facilities around the world. Hydrometallurgical processes are considered the most promising for lithium recovery. But lithium can also be recovered by leaching the slag generated in pyrometallurgical processes, which are widely used for cobalt and nickel recovery. Despite the associated losses, the lithium content present in batteries and even in slag is comparable to, or even higher than, that found in spodumene (Kresse et al., 2025; Brückner et al., 2020).

Replaceability

A variety of promising energy storage solutions is under research and development as alternative battery technologies to lithium-ion batteries (LIBs) Among these, sodium ion batteries (SIBs), magnesium ions (MIBs) and zinc ions (ZIBs) stand out, alongside emerging technologies like solid-state batteries and redox flow batteries (RFBs) (Stephan et al., 2023).

Some of these alternative technologies show significant potential for specific applications, depending on their technical, economic or environmental properties. However, most of them are still in the early stages of technological maturity, exhibiting limitations in operational stability, consistent performance, and industrial scalability. Furthermore, the large-scale adoption of these technologies hinges on the development of appropriate production infrastructure and the implementation of robust supply chains. These conditions are essential to enable production volumes compatible with energy demands on the order of gigawatt-hours (GWh).

Given this scenario, lithium-ion batteries (LIBs) are expected to continue playing a dominant role in the near future. It is anticipated, however, that the battery market will become increasingly diversified, where multiple technologies will coexist, each complementing LIBs by targeting specific applications.

2.3. Rare Earth Elements: neodymium (Nd), praseodymium (Pr), dysprosium (Dy) and terbium (Tb)

Among the 17 CSMs, four were selected for this study: neodymium (Nd), praseodymium (Pr), dysprosium (Dy) and terbium (Tb). These elements are essential for the energy transition, as they are magnetic REEs used to manufacture permanent magnets, which are fundamental for the operation of electric vehicle engines, wind turbine generators, and other low-carbon technologies.

Brazil's Mineral Endowment

According to the Brazilian Critical and Strategic Minerals Potential Overview (SGB-PDAC, 2025), Brazil's major REE occurrences are associated with alkaline-carbonatite rocks and the weathering[25] mantle of granitic rocks:

25. Weathering refers to the physical and chemical changes to which rocks and minerals are subjected on the Earth's surface.

- **Alkaline-carbonatite rocks:** Poços de Caldas (MG), Araxá (MG), Catalão (GO), Tapira (MG), Seis Lagos (AM), among others.
- **Granitic rocks:** Pela-Ema (GO), Bluebush (TO), Iporá (GO), Capão Bonito (SP), Pitinga (AM), among others.

Other types of occurrence include:

- **Sedimentary deposits:** Itapemirim (ES), São Francisco do Itabapoana (RJ).

The Pela-Ema deposit in Minaçu, Goiás, operated by Serra Verde Mineração, is noteworthy because it is the first operational site in Brazil for REE extraction from ion-adsorption clays (IAC) - a type of deposit that is also common in southern China.

The company plans to produce 5,000 tonnes of REE oxides (TREO) in the first phase of the project. The published reserves total approximately 300 Mt of clay with an average grade of 0.15% REEs + yttrium.

Main Projects and Companies in Brazil

Brazil's major REE deposits are shown on the map and listed in the table below:

Figure 9. Map showing the location of major REE deposits

Table 10. Brazil's major REE deposits[26]

DEPOSIT	COMPANY	RESOURCES	GRADE (TREO*)	STATUS
Pela Ema	Serra Verde Pesquisa e Mineração	911 Mt[1]	1200 ppm[1]	In Production
Carina	Aclara Resources	298 Mt[2]	1452 ppm[2]	In Research
Ema	Brazilian Critical Minerals	943 Mt[3]	716 ppm[3]	In Research
PCH Project	Appia Rare Earth & Uranium	46.2 Mt[4]	2,888 ppm[4]	In Research
Caldeira	Meteoric Resources NL	1108 Mt[5]	2413 ppm[5]	In Research

26. The table presented is not intended to list all REE occurrences in Brazil, but rather to highlight the projects considered most relevant. For this selection, the robustness of resource and grade information disclosed in stock exchange releases or corporate reports was evaluated, along with the level of advancement of the projects — including licensing studies and the status of mining processes at the ANM — and the historical or strategic importance of certain deposits. Including all known deposits would excessively expand the table and undermine its concise character.

Colossus	Viridis Mining	201 Mt[6]	2,590 ppm[6]	In Research
Araxá	St George Mining	40.6 Mt[7]	4.13 ppm7	In Research
Bluebush	Alvo Minerals	-	-	In Research
Apuí	Brazilian Critical Minerals	-	-	In Research
Pitinga	Mineração Taboca	-	-	In Research
Bom Futuro	Canada Rare Earth	-	-	In Research
Corrente	Axel REE Limited	-	-	In Research
Iporá	Alvo Minerals	-	-	In Research
Itiquira	Axel REE Limited	-	-	In Research
Catalão II	CMOC Brasil	-	-	In Research (byproduct)
Coda	Enova Mining	-	-	In Research
Capão Bonito	PVW Resources	-	-	In Research
Juquiá	Enova Mining	-	-	In Research
Caladão	Axel REE Limited	-	-	In Research
Itapemirim	-	-	-	Inactive
São Francisco do Itabapoana	-	-	-	Inactive
São Francisco do Itabapoana	-	-	-	Inativo

*T.R.E.O.: Total Rare Earth Oxides. Sources - 1: Serra Verde Mineração (2016); Pinto-Ward (2017); 2: Aclara Resources (2023), (2025); 3: Brazilian Critical Minerals (2025); 4: Appia Rare Earths and Uranium Corp, 2024; 5: Meteoric Resources NL (2025); 6: Viridis Mining and Minerals Ltd. (2024); 7: St George Mining Limited (2024).

Value Chain

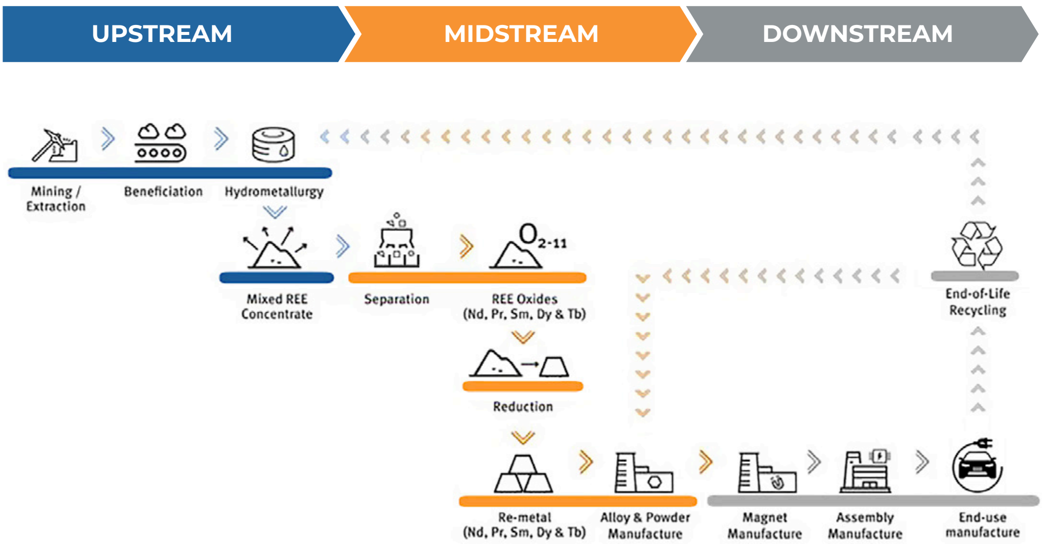
The REE value chain in Brazil begins with the mining of ion-adsorption clays. In ion-adsorption deposits, REEs are not found as distinct minerals. Instead, they are adsorbed onto the surfaces of clay particles and held there by ionic bonds. To extract REEs, the clay must undergo a leaching step. Sodium and ammonium salts have proven particularly effective for this purpose, as they facilitate the necessary ion exchange, releasing the REEs into the aqueous phase. However, other cations such as aluminum and iron are also released during the leaching stage, which compromises the purity of the leachate. The extraction efficiency of the leaching process varies depending on both the specific REE ions and the method employed.

The leachate, now enriched with REE complexes, is then subjected to chemical precipitation in alkaline solutions such as sodium or ammonium hydroxide, which converts the REE ions into insoluble hydroxides.

After precipitation, the mixed REE hydroxides are collected by filtration and washed to remove residual impurities. The resulting precipitates are then ready for further separation and refining to isolate the individual oxides of each rare earth element.

The separated oxides are converted into their metallic form through metallothermic reduction or electrolytic processes.

Figure 10. REE value chain



Estimation of TREO content in the resource

Table 11 shows the estimated total mixed REE oxides, excluding losses during the extraction and precipitation processes. The total REE oxide (TREO) content from the reported resources of producing and research-stage deposits amounts to 5.5 million tonnes.

Current technology and industrial practices limit the recovery of REE from ore to 50%-80% (McNulty et al., 2022). The significant variation in REE extraction efficiency, observed both across recovery methods and among individual elements, stems from differences in their chemical properties, such as variations in ionic radii and charge density, which influence the strength of their interaction with the extraction reagents. Moreover, some elements occur at low concentrations in REE ores, making their extraction even more challenging (Azimi, 2025). For this reason, the content of the separated REE oxides was not calculated.[27]

Table 11. Calculation of the estimated TREO content in the resource[28]

DEPOSIT	TYPE OF DEPOSIT	COMPANY	STATUS	RESOURCES (Mt)	TREO* (ppm)	TREO (Mt)
Pela Ema	IAC (granitoid)	Serra Verde Pesquisa e Mineração	In Production	911	1200	1.093
Carina	IAC (granitoid)	Aclara Resources	In Research	298	1452	0.433
Ema	IAC (felsic volcanic)	Brazilian Critical Minerals	In Research	943	716	0.675
PCH Project	IAC (granitoid)	Appia Rare Earth & Uranium	In Research	46.2	2888	0.133
Caldeira	IAC (alkaline)	Meteoric Resources NL	In Research	1108	2413	2.674
Colossus	IAC (alkaline)	Viridis Mining	In Research	201	2590	0.521
Araxá	Alkaline complex	St George Mining	In Research	40.6	4.13	0.00017
Rocha da Rocha/ Amargosa	IAC (alkaline)	Brazilian Rare Earths	In Research	510.3	1513	772.08
TOTAL				**4058.1**		**6300.96**

Recyclability

Secondary REEs can be recovered through the recycling of electronic waste, sourced from a variety of items including printed circuit boards (PCBs), mobile phone panels, NdFeB permanent magnets, depleted fluorescent lamps, and nickel-metal hydride (NiMH) batteries. Different recovery technologies are being developed and investigated, with a focus on pyrometallurgical and hydrometallurgical processes, and, more recently, methods based on solvent extraction.

27. These calculations were based on total reported resources, excluding losses in the processing stages. For more information, see Appendix A — Methodology.

28. The chemical processes used for the separation and purification of rare earth elements are complex and costly because these elements are typically co-extracted from ores. This may lead to market imbalances - an excess supply of certain elements coupled with a scarcity of others - which significantly complicates the economics of production. The presence of higher concentrations of desirable and valuable elements, or the absence of less valuable and contaminating elements, can make extraction more economical and technically feasible. Conversely, ores with low concentrations of these elements or with complex impurities make the extraction process more expensive and less advantageous, potentially rendering the project unfeasible. Neodymium is the most sought-after rare earth element, followed by cerium and lanthanum.

Replaceability

REEs possess unique electrical, magnetic, chemical and physical properties that make them essential for advanced technologies, such as the production of high-performance permanent magnets, optoelectronic devices, lasers, catalysts, sensors and high-efficiency electronic components.

The growing risk associated with the concentration of global production of these elements, coupled with environmental concerns and price volatility, has driven research and development into alternative materials. Some of these solutions have already demonstrated technical and industrial viability. A promising example is iron-nitrogen-based alloys, such as iron nitride. These alloys exhibit magnetic properties that are comparable or even superior to those of REE-based magnets, while being composed entirely of abundant and lower-cost elements.

Another significant development is tetraenite, an iron-nickel alloy with permanent magnetism. Although originally found only in meteorites, recent advances in synthesis have enabled its laboratory production, opening up possibilities for its commercial use as a partial substitute for neodymium- or samarium-based magnets.

Beyond direct substitution with alternative functional materials, research is focusing on technological strategies seeking to redesign devices and systems so as to reduce or eliminate the need for REEs while maintaining technical performance.

2.4. Nickel

Nickel is a transition metal, characterized primarily by its corrosion resistance, toughness, and ductility, making it essential in the production of metallic alloys. Approximately 65% of global demand for nickel is directed toward the production of stainless steels.

Nickel has a wide range of uses, with applications in the chemical, shipbuilding and food industries. It is used in alloys with chromium, iron and copper, which are employed in aircraft turbines, thermal power plants, and oil and gas equipment, because of its ability to withstand high temperatures and pressures. Nickel is also used in electroplating, as a protective or decorative coating for metals, owing to its shiny appearance and resistance to oxidation. In technology sectors, it is integral to the defense, aerospace, and nuclear industries. It is also an essential input for the cathodes of high-energy-density rechargeable batteries.

Brazil's Mineral Endowment

Brazil ranks among the top ten global producers of nickel, with a reported output of 82,700 tonnes in 2023 and 77,000 tonnes in 2024.

With reserves totaling 16 million tonnes, Brazil ranks third globally in reserve volume, behind only Indonesia (1st) and Australia (2nd) (USGS, 2025).

Brazil currently has four operating mines and several exploration prospects at different stages of development. Nickel ore is extracted from both sulfide and lateritic deposits.

Class I nickel, defined by its high purity, is the type most commonly used in rechargeable battery production. Although it is typically sourced from sulfide deposits because these ores allow for more efficient hydrometallurgical and pyrometallurgical processing, this relationship reflects a technological and economic trend rather than a strict rule.

Lower-purity class II nickel is generally derived from lateritic ores, which have lower grades and are economically viable for applications that do not require very high purity, such as the production of stainless steel. With advances in processing technologies, however, it is possible that in the future, class I nickel may also be produced from lateritic ores.

Brazilian deposits are mostly lateritic nickel, with projects in operation in Pará, Goiás and Bahia.

Main Projects and Companies in Brazil

Brazil's major deposits are shown on the map and listed in the table below:

Figure 11. Map showing the location of major nickel deposits

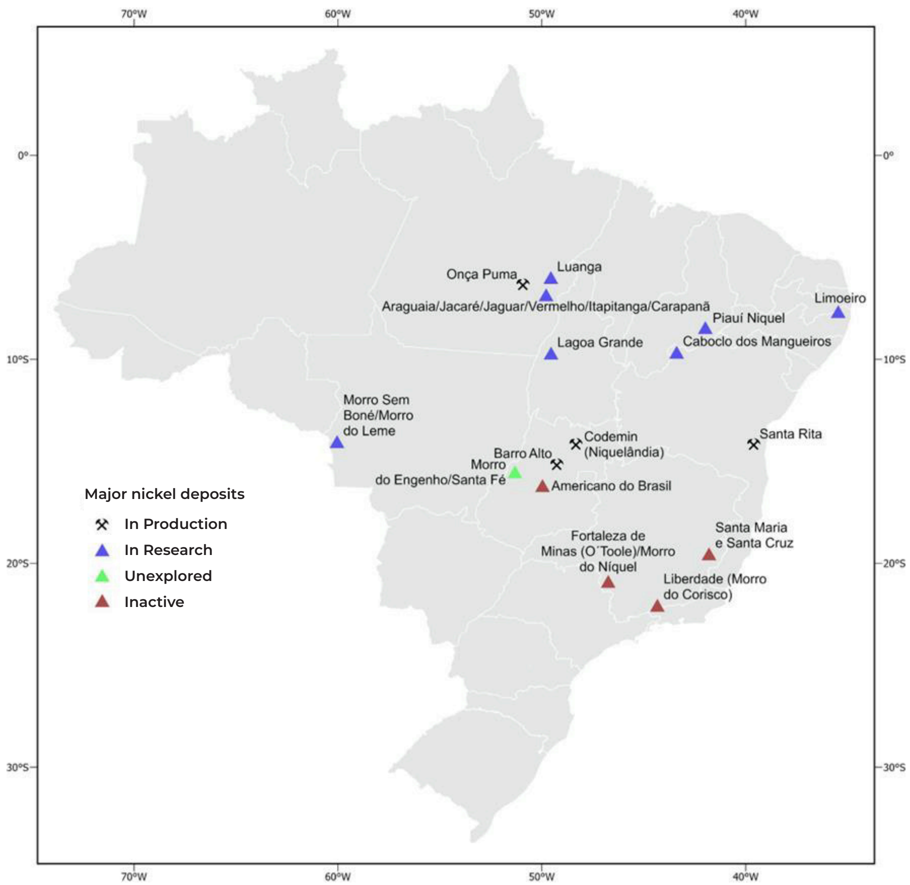


Table 12. Brazil's major nickel deposits

DEPOSIT	ORE	COMPANY	RESOURCES (Mt)	GRADE (Ni) %	STATUS
Americano do Brasil	Ni, Cu, Co	Prometálica Mineração Centro Oeste S.A.	3.09	N/A	Inactive
Araguaia	Ni, Co, Fe, MgO, SiO2, Al2O3, Cr2O3	Horizonte Minerals	132.3	1.26%	Inactive
Barro Alto	Ni	MMG Limited	23.8	1.21 %	In Production
CODEMIN (Niquelândia)	Ni	MMG Limited	2.5	1.25 %	In Production
Fortaleza de Minas (O'Toole)	Ni, Cu, Co	N/A	45.45	N/A	Inactive
Itapitanga	Ni, Co , Sc	Centaurus Metals	40	0.95 %	In Research

Jacaré	Ni, Co	MMG Limited	99.7	1.31 %	In Research
Jaguar	Ni, Cu, Co	Centaurus Metals	112.6	0.87 %	In Research
Lagoa Grande	Ni, Cu, Co	CBPM	405	0.16 %	In Research
Liberdade (Morro do Corisco)	Ni	N/A	1	N/A	Inactive
Limoeiro	Ni, Cu, Pt	CBA	35	N/A	In Research
Luanga	EGP, Au, Ni	Bravo Mining Corp.	236	0.12%	In Research
Caboclo dos Mangueiros	Ni, Cu, Co	Bahia Nickel	200	N/A	In Research
Morro do Engenho	Ni, Co, Sc	SGB-CPRM	67.24	1.07 %	Unexplored
Morro do Leme	Ni, Fe, SiO2, MgO	Anglo American Níquel Brasil Ltda.	18	1.73 %	In Research
Morro do Níquel	Ni	N/A	2.3	1.5 %	Inactive
Morro Sem Boné	Ni, Fe, SiO2, MgO	Anglo American Níquel Brasil Ltda.	40.287	1.79 %	In Research
Mundial Carapanã	Ni	N/A	30	1.4 %	In Research
Niquelândia	Ni, Co	CBA	55	0.94 %	Inactive
Onça-Puma 1	Ni, Co, Fe, SiO2, MgO	Vale Base Metals	142.5	1.45%	In Production
Piauí Níquel	Ni, Co	Brazilian Nickel Ltda.	98.8	0.84 %	In Research
Santa Fé	Ni, Co, Sc	SGB-CPRM	39.73	1.14 %	Unexplored
Santa Rita (Fazenda Mirabela)	Ni, Cu, Co	Atlantic Nickel/ CBPM	255.1	0.5 %	In Production
Vermelho (V1 and V2)	Ni, Co, Fe2O3, MgO2, SiO2	Horizonte Minerals	148.8	1.05 %	Inactive
Santa Maria e Santa Cruz	Ni, Co	N/A	N/A	N/A	Inactive

Sources: 1 - Vale S.A. 2024

Value Chain

The value chain for sulfide ores centers on the production of electrolytic nickel. The process begins with beneficiation, where the ore is concentrated. The concentrated material then undergoes a sulfur oxidation step, typically carried out in flash or rectangular furnaces, which yields matte, a metallic alloy composed primarily of sulfides. The slag generated during this process is treated separately in an electric furnace to recover any residual sulfides. The matte can either be sold as an intermediate product or sent for further refining, which involves acid leaching (with H_2SO_4) to solubilize the metals. Subsequently, solvent extraction (SX) and electrolysis are employed to obtain metallic cathodes, such as nickel and cobalt. Any residual metals are then precipitated and directed to specific treatment processes.

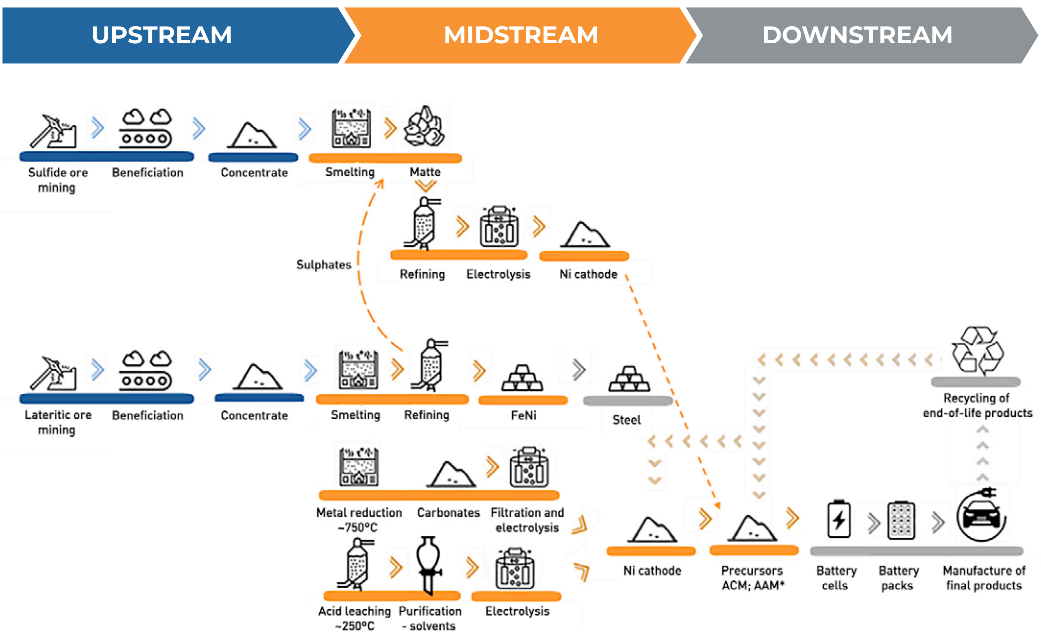
Lateritic ores are primarily used in the production of ferro-nickel and electrolytic nickel through three main routes: pyrometallurgy, hydrometallurgy and pressure acid leach (PAL).

In the pyrometallurgical process, the ore is crushed and smelted in electric furnaces. The resulting metal is then refined to remove impurities such as sulfur and phosphorus. Sulfur is sometimes recovered and utilized in matte production, which subsequently follows the established sulfide ore processing route.

In the hydrometallurgical route, the ore is crushed, ground, dried and reduced in vertical furnaces, forming metal carbonates that go through filtration and electrolysis stages to yield pure nickel cathodes.

In the PAL process, the ore is crushed, washed and subjected to acid leaching under high temperature and pressure (approximately 250°C). The resulting liquor, separated by decantation, is purified using solvent extraction to recover cobalt first, and then nickel. The final stage is electrolysis, which produces metal cathodes.

Figure 12. Nickel value chain



Estimation of nickel content in the resource

The nickel content from the reported resources of producing deposits amounts to 3.66 million tonnes. The theoretical total of nickel across all categories of reported deposits (in production, in research, unexplored, and inactive) amounts to 12.77 million tonnes. This estimation excludes process losses.

Table 13. Calculation of the estimated nickel content in the resource[29] [30]

DEPOSIT	COMPANY	STATUS	ORE	RESOURCE (Mt)	GRADE (Ni) %	Ni (Mt)
Barro Alto	Anglo American Níquel Brasil Ltda.	In Production	Ni	23.8	1.21	0.29
CODEMIN (Niquelândia)	Anglo American Níquel Brasil Ltda.	In Production	Ni	2.5	1.25	0.03
Onça-Puma[1]	Vale Base Metals	In Production	Ni, Co, Fe, SiO_2	142.5	1.45	2.07
Santa Rita (Fazenda Mirabela)	Atlantic Nickel/ CBPM	In Production	Ni, Cu, Co	255.1	0.5	1.28
Araguaia	Horizonte Minerals	In Research	Ni, Co, Fe, MgO, SiO_2, Al_2O_3, Cr_2O_3	132.3	1.26	1.67
Itapitanga	Centaurus Metals	In Research	Ni, Co , Sc	4.0	0.95	0.38
Jacaré	Anglo American Níquel Brasil Ltda.	In Research	Ni, Co	99.7	1.31	1.31
Jaguar	Centaurus Metals	In Research	Ni, Cu, Co	112.6	0.87	0.98
Lagoa Grande	CBPM	In Research	Ni, Cu, Co	405	0.16	0.65
Limoeiro	CBA	In Research	Ni, Cu, Pt	35	N/A	
Luanga	Bravo Mining Corp.	In Research	EGP, Au, Ni	236	0.12	0.28
Caboclo dos Mangueiros	Bahia Nickel	In Research	Ni, Cu, Co	200	N/A	
Morro do Leme	Anglo American Níquel Brasil Ltda.	In Research	Ni, Fe, SiO_2, MgO	18	1.73	0.31
Morro Sem Boné	Anglo American Níquel Brasil Ltda.	In Research	Ni, Fe, SiO_2, MgO	40.287	1.79	0.72
Mundial Carapanã	N/A	In Research	Ni	30	1.4	0.42
Piauí Níquel	Brazilian Nickel Ltda.	In Research	Ni, Co	98.8	0.84	0.83
Vermelho (V1 and V2)	Horizonte Minerals	In Research	Ni, Co, Fe_2O_3, Mg_{O2}, SiO_2	148.8	1.05	1.56
Morro do Engenho	SGB-CPRM	Unexplored	Ni, Co, Sc	67.24	1.07	0.72
Santa Fé	SGB-CPRM	Unexplored	Ni, Co, Sc	39.73	1.14	0.45

29. The calculation covered the research and production phases, excluding reserves that are presently inactive.

30. These calculations were based on total reported resources, excluding losses in the processing stages. For more information, see Appendix A — Methodology.

Americano do Brazil	Prometálica Mineração Centro Oeste S.A	Inactive	Ni, Cu, Co	3.09	N/A	
Fortaleza de Minas (O'Toole)	N/A	Inactive	Ni, Cu, Co	45.45	N/A	
Liberdade (Morro do Corisco)	N/A	Inactive	Ni	1	N/A	
Morro do Níquel	N/A	Inactive	Ni	2.3	1.5	0.03
Niquelândia	CBA	Inactive	Ni, Co	55	0.94	0.52
Santa Maria and Santa Cruz	N/A	Inactive	Ni, Co	N/A	N/A	
TOTAL IN PRODUCTION						**3.66**
TOTAL IN RESEARCH						**9.11**
GRAND TOTAL						**12.77**

Recyclability

Nickel is a valuable material for the circular economy because it can be fully and repeatedly recycled without loss of quality. Its intrinsic value drives high recycling rates, with a significant portion of products containing nickel - particularly stainless steel - being recovered and reused at the end of their life cycle.

It is currently estimated that around 68% of the nickel used in stainless steels and other metal products is recycled. The recycling of lithium-ion batteries is another significant source of secondary nickel. Because of nickel's value, a significant portion of nickel-containing products is effectively collected and directed to recycling.

Replaceability

Nickel can be partially substituted in certain applications, primarily for economic, environmental and supply security reasons.

In stainless steels, it can be replaced by manganese, nitrogen or copper, albeit with loss of performance. Alternatives for high-temperature superalloys include elements such as molybdenum, tungsten, cobalt and tantalum, but they typically are more expensive or difficult to process. In batteries, particularly with the advancement of LFP (lithium iron phosphate) technologies, there is a push to reduce dependence on nickel, despite the lower energy density. In catalysts, cobalt and rhodium can serve as substitutes under specific conditions.

Although partial alternatives exist, nickel remains a strategic metal in various industries because its unique combination of properties makes its complete substitution difficult in critical applications.

2.5. Niobium

Niobium (Nb) is a strategic element widely used in the production of high-performance alloys, particularly in the steel and aerospace industries. It is used primarily as an additive in special steels, where very small amounts (typically <0.1%) significantly enhance mechanical strength, weldability and corrosion resistance.

Niobium facilitates the energy transition by helping produce lighter and stronger structures, including wind turbines, electric vehicle chassis, and high-pressure pipelines.

Brazil's Mineral Endowment

Brazil boasts the world's largest reserves of niobium, concentrated mainly in Araxá, Minas Gerais, home to the world's largest mine, operated by CBMM.

Niobium occurrences are primarily associated with carbonatites (Araxá, Catalão), alkaline complexes (Seis Lagos), and A-type granites (Pitinga). In Equador (RN), niobium occurs in pegmatites of the Borborema Pegmatite Province.

The Araxá mine, operated by CBMM (Companhia Brasileira de Metalurgia e Mineração) and St George Mining Ltd, is the world's largest producer of ferroniobium, with an annual production capacity in excess of 100,000 tonnes of oxide equivalents. The company accounts for approximately 80% of global production. The average grade of the Araxá ore is around 0.68% Nb2O5 (St George Mining Ltd, 2025).

The Catalão mines (Mine I and Mine II) in Goiás are operated by CMOC International, producing ferroniobium from carbonatite mineralizations. The resources are estimated at 148.9 million tonnes (~1.02% Nb2O5) and 156.6 million tonnes (~0.34% Nb2O5) (CMOC Group Limited, 2025).

Main Projects and Companies in Brazil

Brazil's major deposits are shown on the map and listed in the table below:

Figure 13. Map showing the location of major niobium deposits

Table 14. Brazil's major niobium deposits

DEPOSIT	COMPANY	RESOURCES	GRADE (Nb_2O_5)	STATUS
Araxá	CBMM	41.2 Mt[1]	0.68%[1]	In Production
Catalão I	CMOC	148.9 Mt[2]	1.02%[2]	In Production
Catalão II	CMOC	156.6 Mt[2]	0.34%[2]	In Production
Seis Lagos	Taboca (Minsur)	28.3 Mt[3]	2.97%[3]	In Research
Equador	Summit Minerals / Power Minerals	NA	up to 30.34%[4]	In Research
Pitinga	Mineração Taboca	NA	NA	Production (Sn co-product)
Santa Anna	Edem + Power Minerals	NA	3.36%[5]	In Research

Sources: 1- St George Mining Ltd (2025); 2- CMOC Group Ltd (2024); 3- Bento et al. (2022); 4- Summit Minerals (2024); 5- Power Minerals (2024)

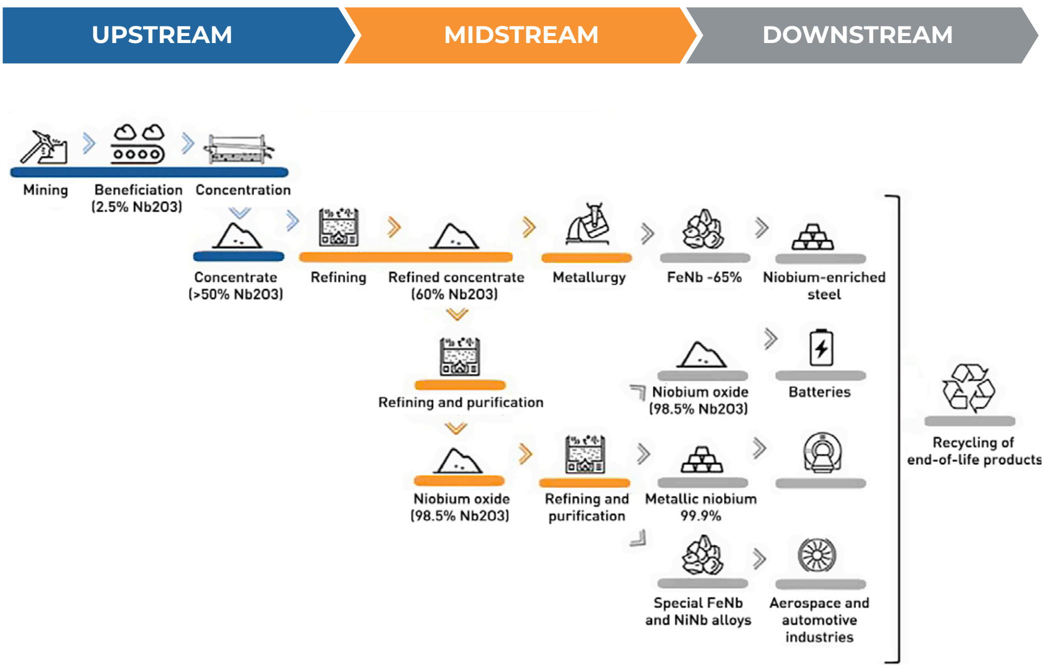
Value Chain

In Brazil, niobium is primarily extracted from pyrochlore. The niobium value chain starts with mining. The ore then goes through homogenization and concentration stages and is refined to remove impurities. The refined concentrate (Nb2O5, 60%) can either be processed through metallurgy to produce (i) ferroniobium (FeNb) or go through an additional refining stage to produce (ii) high-purity niobium oxide.

FeNb is crushed, sorted and marketed worldwide, primarily as a raw material for the production of niobium-enriched steel.

High-purity niobium oxide is further processed through different routes to yield (iii) optical-grade niobium oxides (99.5%), which are used in the manufacture of optical lenses, hydrogen cells, batteries and other applications; (iv) special vacuum-grade alloys of ferroniobium and nickel-niobium, which are inputs for the aerospace and automotive industries; and (v) metallic niobium (99.9% Nb), widely utilized in magnetic resonance imaging (MRI) equipment and particle accelerators.

Figure 14. Niobium value chain



Brazil's dominance over the niobium supply chain, from mining to the beneficiation and export of high-value alloys, leverages Brazil's strategic role in the global supply of this critical resource.

Estimation of niobium content in the resource

The niobium pentoxide (Nb2O5) content from the reported resources of producing and research-stage deposits amounts to 3.17 Mt. This total corresponds to the theoretical production of 3.50 Mt of ferroniobium (FeNb) or 2.22 Mt in metallic niobium (Nb). This estimation excludes process losses.

Table 15. Calculation of the estimated niobium content in the resource[31]

DEPOSIT	COMPANY	STATUS	RESOURCE (Mt)	GRADE (Nb_2O_5) %	Nb_2O_5	FeNb (Mt)	Nb (Mt)
Araxá	CBMM	In Production	41.2	0.68	0.28	0.31	0.20
Catalão I	CMOC	In Production	148.9	1.02	1.52	1.68	1.06
Catalão II	CMOC	In Production	156.6	0.34	0.53	0.59	0.37
Pitinga	Mineração Taboca	Production (Sn co-product)	NA	NA			
Seis Lagos	Taboca (Minsur)	In Research	28.3	2.97	0.84	0.93	0.59
Equador	Summit Minerals / Power Minerals	In Research	NA	30.34			
Santa Anna	Edem + Power Minerals	In Research	NA	3.36			
TOTAL					**3.17**	**3.50**	**2.22**

Recyclability

The difficulty in separating and recovering niobium from alloys, especially those with low concentrations, makes its secondary recycling challenging. While the co-recycling of niobium along with steel is common, the process results in dilution of the niobium content within the new alloy, which makes it difficult to achieve the required concentrations for specific applications.

31. These calculations were based on total reported resources, excluding losses in the processing stages. For more information, see Appendix A — Methodology.

Replaceability

Although niobium possesses unique properties, such as high mechanical strength, excellent weldability and thermal stability, it can be successfully replaced by other metals and materials in certain applications, particularly in the production of high-strength steels and alloys. The main substitutes include vanadium, titanium and tantalum, as well as microalloyed steels and other advanced alloys that include these elements.

Although viable substitutes do exist, niobium remains a strategic element across various industrial and technology applications because of the balance between its mechanical performance, corrosion resistance, cost and processing feasibility ensures that.

2.6. Copper

Copper (Cu) is considered one of the first metals manipulated and worked by humankind, with its documented use dating back over 10,000 years. It remains one of the most strategic minerals in the contemporary world, playing a crucial role in the energy transition, the digitalization of the economy, and modern infrastructure. Thanks to its physical and chemical properties, such as high electrical and thermal conductivity, malleability, ductility, and corrosion resistance, copper is a key material for the implementation of clean energy technologies.

Brazil's Mineral Endowment

Brazil's highly varied copper deposits are primarily associated with sulfide and oxide mineralizations. The main ore minerals include chalcopyrite, chalcocite and bornite in sulfide deposits, and malachite in oxide deposits.

Brazil's reserves and production are concentrated in the Carajás mineral province (PA), where IOCG-type (iron oxide copper gold) deposits predominate, for instance, in the Salobo mine, operated by Vale. These deposits show average grades around 0.6% copper and account for the majority of Brazil's copper production.

The porphyry-type deposits found in Goiás are of lesser economic significance compared to the major systems in the Andean region, the United States, and Southeast Asia, and there is no significant production coming from these deposits in Brazil.

Magmatic and hydrothermal deposits have been identified in other regions, such as Bahia and Alagoas, and VMS (volcanogenic massive sulfide), SEDEX and sediment-hosted deposits are also known to occur. This further shows how geologically diverse copper is in Brazil (ANM, 2024a; SGB, 2025).

Main Projects and Companies in Brazil

Brazil's major deposits are shown on the map and listed in the table below:

Figure 15. Map showing the location of major copper deposits

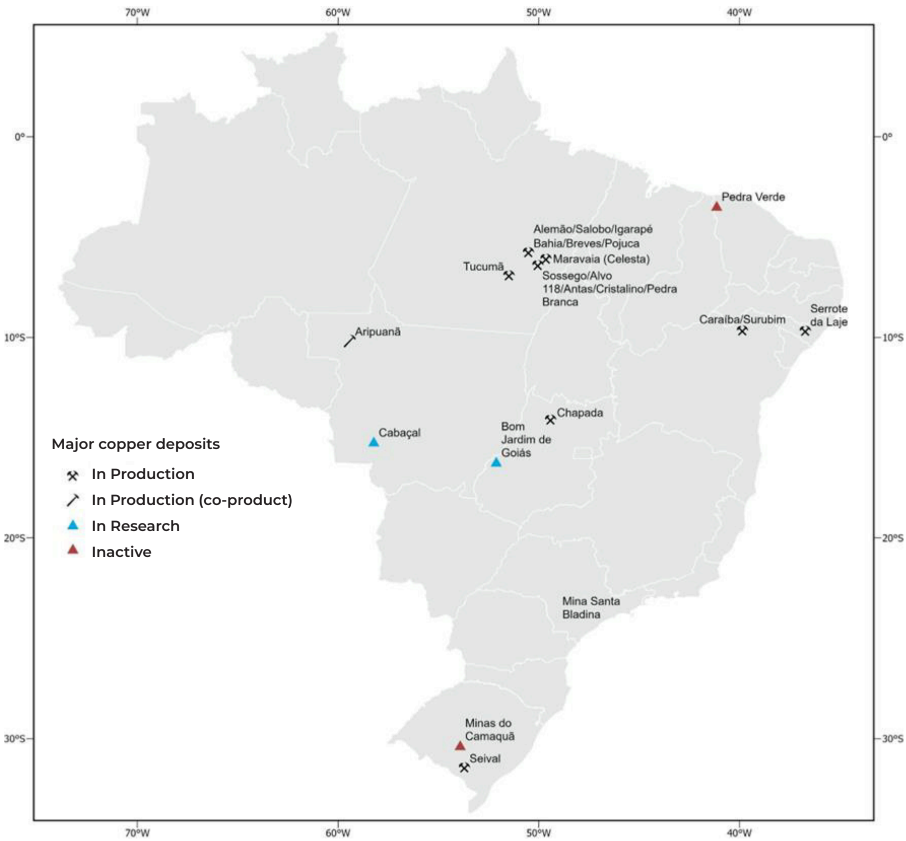


Table 16. Brazil's major copper deposits

DEPOSIT	ORE	COMPANY	RESOURCES	GRADE (Cu) %	STATUS
Alemão[1]	Cu-Au	Vale S.A.	139.1 Mt	1.54%	In Production
Antas Norte and Sul	Cu-Au	BHP Group Limited	1.5 Mt	0.5%	In Production
Breves	Cu-Au-Ag	Vale S.A.	50 Mt	1.22%	In Production
Cabaçal[6]	Cu-Au-Ag	Meridian Mining	51.69 Mt	0.4%	In Research
Caraíba[2]	Cu	Ero Copper	262.52 Mt	0.84%	In Production
Chapada[5]	Cu-Au	Lundin Mining Corp	1067.01 Mt	0.22%	In Production
Furnas[1]	Cu-Au	Ero Copper/Vale S.A.	313.6 Mt	0.6%	In Research
Pantera	Cu-Au	BHP Group Limited	20.0 Mt	1.2%	In Research
Paulo Afonso, Pojuca, Gameleira, Grota Funda[1]	Cu-Au	Vale S.A.	1407.5 Mt	0.57%	In Research
Pedra Branca[4]	Cu-Au	BHP Group Limited	11.4 Mt	1.65%	In Production
Pedra Verde	Cu	Pedra Verde	44.2 Mt	0.9%	Inactive
Salobo[1]	Cu-Au	Vale S.A.	1693.2 Mt	0.61%	In Production
Saúva[5]	Cu-Au	Lundin Mining Corp.	277.07 Mt	0.31%	In Research
Seival	Cu-Ag	Seival	0.2 Mt	N/A	In Production
Serrote da Laje	Cu-Au	Mineração Vale Verde Ltda	119.2 Mt	0.5%	In Production
Sequeirinho, Cristalino, Mata II, Bacaba, Barão, 118, Visconde[1]	Cu-Au	Vale S.A.	887.1 Mt	0.63%	Production/ In Research[32]
GT-46/Igarapé Cinzento	Cu-Au	GT-46/Igarapé Cinzento	N/A	N/A	In Research
Maravaia (Celesta)	Cu-Au	Maravaia (Celesta)	N/A	N/A	In Production

Sources: 1 - Vale S.A. 2024; 2 - https://erocopper.com/operations/caraiba-operations/; 3 - https://erocopper.com/operations/tucuma-project/; 4-BHP,2024 https://www.sec.gov/ix?doc=/Archives/edgar/data/811809/000119312524210297/d812514d20f.htm; 5 - Lundin Mining, 2025 https://lundinmining.com/news/lundin-mining-announces-2024-mineral-resource-and-123185/; 6 - Meridian Mining, 2025.

Value Chain

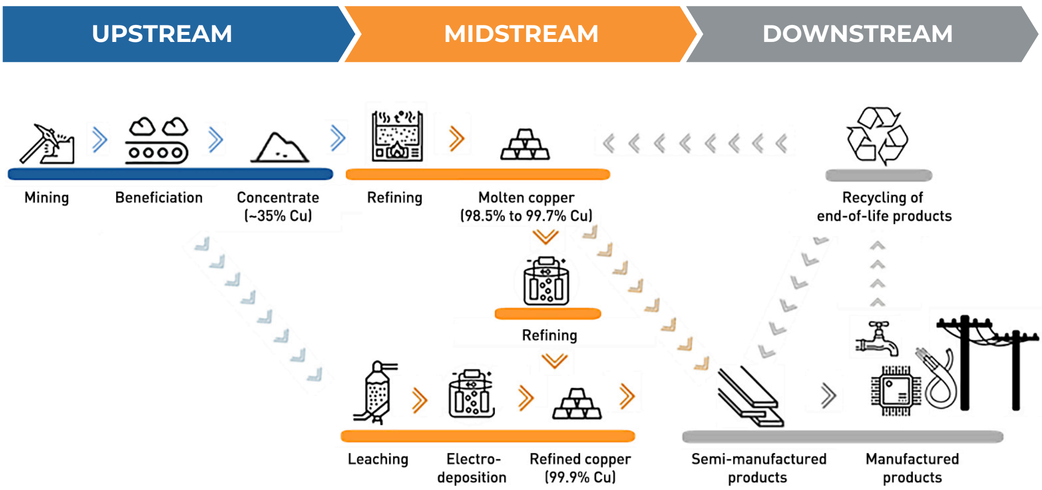
The first stages of the copper value chain, following mining, will vary depending on the type of ore. The copper extraction process for high-grade sulfide ores begins with concentration (crushing, screening, grinding and flotation). This stage produces a concentrate with 25-35% copper grade. In the next step, the copper is partially purified through thermal processes, resulting in molten copper (99.7% purity). A new electrolytic refining stage can increase the purity

32. Sequeirinho and Mata II are in production, while 118, Bacaba, Barão, Cristalino and Visconde are in research

level to 99.9% (cathode grade). This pyrometallurgical route allows for the recovery of metallic by-products, such as gold, silver and cobalt.

Oxidized, silicate and low-grade ores are treated through hydrometallurgical processes. This route involves leaching the ore with acids, to dissolve the copper, followed by concentration stages (such as cementation with iron or solvent extraction) and electrodeposition. The combination of solvent extraction and electrodeposition is known as the SX-EW process, which yields 99.9% pure copper. Although efficient, the hydrometallurgical route has limitations when it comes to by-product recovery.

Figure 16: Copper value chain



Estimation of copper content in the resource

The copper content from the reported resources of producing deposits amounts to only 32.54 million tonnes. The theoretical total copper content from producing and research-stage deposits amounts to 35.73 million tonnes. This estimation excludes process losses.

Table 17. Calculation of the estimated copper content in the resource[33] [34]

DEPOSIT	COMPANY	STATUS	ORE	RESOURCE (Mt)	GRADE	Cu (Mt)
Alemão	Vale S.A.	In Production	Cu-Au	139.1	1.54	2.14
Antas Norte and Sul	OZ Minerals	In Production	Cu-Au	1.5	0.5	0.01
Breves	Vale S.A.	In Production	Cu-Au-Ag	50	1.22	0.61
Caraíba	Ero Copper	In Production	Cu	262.52	0.84	2.21
Chapada	Lundin Mining Corp	In Production	Cu-Au	1067.01	0.22	2.35
Paulo Afonso, Pojuca, Gameleira, Grota Funda	Vale S.A.	In Production	Cu-Au, Cu-Zn	1407.5	0.57	8.02
Pedra Branca	BHP Group Limited	In Production	Cu-Au	11.4	1.65	0.19
Salobo	Vale S.A.	In Production	Cu-Au	1693.2	0.61	10.33
Seival	Seival	In Production	Cu-Ag	0.2	N/A	
Serrote da Laje	Mineração Vale Verde Ltda	In Production	Cu-Au	119.2	0.5	0.60
Sossego, Cristalino, Mata II, Bacaba, Barão, 118, Visconde)	Vale S.A.	In Production	Cu-Au	887.1	0.63	5.59
Tucumã (Boa Esperança)	Ero Copper	In Production	Cu-Co	59.28	0.85	0.50
Maravaia (Celesta)	Maravaia (Celesta)	In Production	Cu-Au	N/A	N/A	
Cabaçal	Meridian Mining	In Research	Cu-Au-Ag	51.69	0.4	0.21
Furnas	Ero Copper/ Vale S.A.	In Research	Cu-Au	313.6	0.6	1.88
Pantera	OZ Minerals	In Research	Cu-Au	20	1.2	0.24
Saúva	Lundin Mining Corp.	In Research	Cu-Au	277.07	0.31	0.86
GT-46/Igarapé Cinzento	GT-46/Igarapé Cinzento	In Research	Cu-Au	N/A	N/A	
Pedra Verde	Pedra Verde	Inactive	Cu	44.2	0.9	0.40
TOTAL IN PRODUCTION						**32.54**
TOTAL IN RESEARCH						**3.19**
GRAND TOTAL						**35.73**

33. The calculation covered the research and production phases, excluding reserves that are presently inactive.

34. These calculations were based on total reported resources, excluding losses in the processing stages. For more information, see Appendix A — Methodology.

Recyclability

Copper is highly suitable for resource recovery strategies and circular economy initiatives because it is one of the very few materials that maintains its chemical and physical properties even after multiple recycling cycles. According to the International Copper Study Group, approximately 32% of global copper consumption came from recycled materials in 2022.

Replaceability

Copper's high price volatility and costs have driven the search for alternative materials that can replace it in various industrial applications. Copper can be partially replaced by different materials, depending on the technical requirements of each sector.

Standing out among the most studied alternatives, aluminum is the primary option for reducing pressure on copper demand, particularly in electrical equipment and plumbing systems. Graphene's excellent conductivity and thermal stability make it a promising alternative for electrical applications. Optical fiber is widely used as a substitute for copper in telecom applications and several types of plastics are viable alternatives for hydraulic systems. Additionally, materials such as steel, titanium and advanced composites can replace copper in heat exchangers and other thermal applications.

However, copper's natural properties - including its high electrical and thermal conductivity, corrosion resistance, and malleability - and its wide range of industrial applications, continue to raise significant hurdles to its substitution.

2.7. Iron Ore

Iron ore is one of the most abundant and economically significant raw materials on the planet, serving as the primary source for the extraction of iron (Fe). With a silvery color and metallic luster, iron is widely used in industry because of its high mechanical strength, ductility, malleability, thermal conductivity, and its ability to form alloys, particularly with carbon to create steel.

Steelmaking accounts for over 90% of global iron ore consumption. Steel is a key input in the civil construction, the transportation sector, and capital goods industry, and is essential for producing metal packaging and durable consumer goods. Iron is directly used in the form of cast or forged iron to produce motor components, valves, gears and various industrial tools. From a strategic standpoint, iron ore plays a crucial role in production and logistics infrastructure, giving countries with large reserves and production capacity, such as Brazil, a competitive edge in the global supply chain.

Iron ore is a strategic mineral for Brazil and plays a significant role in global infrastructure. The decarbonization of the steel industry is one of the major challenges of the global energy transition. Accounting for approximately 7 to 9% of global CO2 emissions, the sector is seeking technological and operational alternatives to reduce its environmental footprint. The use of high-quality iron ore emerges as a key component in making steel production cleaner and more efficient.

Brazil's Mineral Endowment

Brazil's iron deposits are associated with Lake Superior-type Banded Iron Formations, which are Proterozoic passive margin sedimentary successions predominantly containing hematite as the ore mineral and occurring in the Iron Quadrilateral region of Minas Gerais. Additionally, there are Algoma-type deposits, related to Archaean and Paleoproterozoic volcanosedimentary sequences containing magnetite and hematite, found in Carajás, Pará.

In the Iron Quadrangle, grades can reach up to 49% with nearly 582 Mt run-of-mine (ROM) ore extracted; in Carajás, grades of 65% are obtained with over 174 Mt ROM. In addition to these major regions, production also occurs in Mato Grosso do Sul (11 Mt with 64% grades) and in Bahia (3 Mt with 49% grades). Secondary production takes place in Piauí, Goiás, Ceará and Rio Grande do Norte (ANM, 2024a). Brazil holds the third largest raw ore reserve and the second in ore content, totaling 27 Bt, ranking only behind Australia (USGS, 2024).

The main destinations for Brazilian iron products are China and the United States, both primarily consuming iron ore and its concentrates (ANM, 2024b).

Vale S.A. dominates domestic iron ore mining with a 69% market share, followed by Anglo American with approximately 7%. Large-scale mines and beneficiation plants predominate, and the royalties (CFEM) derived from iron ore account for 83% of Brazil's total mining levies (ANM, 2024a).

Main Projects and Companies in Brazil

Brazil's major deposits are shown on the map and listed in the table below:

Figura 17. Map showing the location of major iron ore deposits

Table 18. Brazil's major iron ore deposits

DEPOSITS		COMPANY	RESOURCES*	GRADE	STATUS
Northern System[1]	Serra South (S11C and S11D)	Vale S.A.	4414.3 Mt	65.42%	In Production
	Serra North	Vale S.A.	3286 Mt	65.64 %	In Production
	Serra East	Vale S.A.	880.8 Mt	57.98 %	In Production
	Serra do Rabo	Vale S.A.	578.8 Mt	66.04%	In Production
Southeastern System[1]	Mariana (Alegria, Sudeste1 Fábrica Nova, Fazendão, Capanema)	Vale S.A.	9066.2 Mt	41.29%	In Production
	Minas Centrais (Brucutu, Morro Agudo, Apolo)	Vale S.A.	4021 Mt	43.68%	In Production
	Itabira (Conceição, Minas do Meio)	Vale S.A.	1498.1 Mt	45.80%	In Production

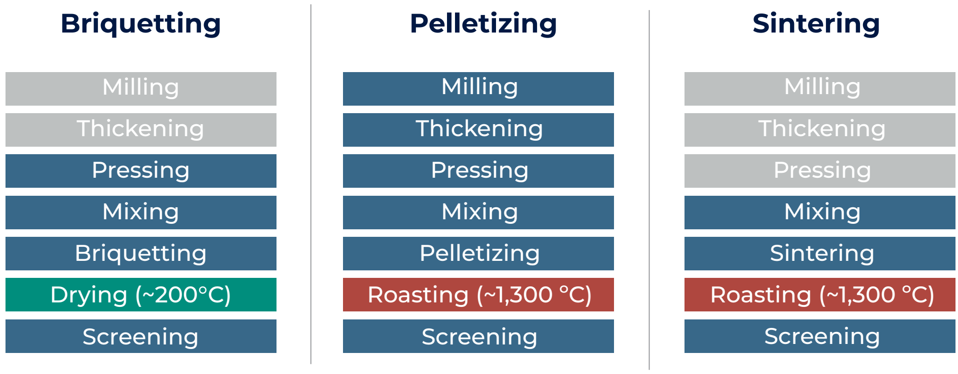
Southern System[1]	Vargem Grande (Sapecado, Galinheiro, Tamanduá, Capitão do Mato, Abóboras)	Vale S.A.	8900.4 Mt	40.42%	In Production
	Paraopeba (João Pereira, Segredo, Mar Azul, Capão Xavier)	Vale S.A.	5325.7 Mt	41.72%	In Production
Minas-Rio (Serra do Sapo, Itapanhoacanga)[2]		Anglo American Minério de Ferro Brasil S.A.	5783.9 Mt	32.72%	In Production
East, Central and West Mines[3]		Mineração Usiminas S.A.	2750 Mt	37.55%	In Production
Minas Andrade e Serra Azul[4]		ArcelorMittal Brasil S.A.	805 Mt	43.65%	In Production
Amapá[5]		Cadence Minerals PLC	276.24 Mt	38.33%	In Research
Alegria Mine (Germano Complex)[8]		Samarco Mineração S.A. (under court-supervised reorganization)	5.2 Bt[6]	N/A	In Production
Casa de Pedra and Engenho		CSN Mineração	6 Bt[7]	N/A	In Production
Fazenda Mocó (Ferro Verde)		Brazil Iron Mineração Ltda.	1.7 Bt[7]	N/A	In Research
Baratinha and Mongais		Bemisa Holding S.A.	>300 Mt[7]	N/A	In Research
Planalto Piauí		Bemisa Holding S.A.	>1.6 Bt7	N/A	In Research
Pedra Branca		Bemisa Holding S.A.	130 Mt	N/A	In Research
Tico-Tico and Ipê Mines		Mineração Morro do Ipê S.A.	N/A	N/A	In Production
Pedra de Ferro Mine		Bahia Mineração	N/A	N/A	In Production
Urucum and Santa Cruz Mines		LHG Mining (formerly Mineração Corumbaense Reunida S.A.)	N/A	N/A	In Production
Pau Branco		Vallourec Tubos do Brasil Ltda	N/A	N/A	In Production
Várzea do Lopes and Miguel Burnier		Gerdau Açominas S.A.	N/A	N/A	In Production
Ferro + Mineração S.A.		Ferro + Mineração S.A.	N/A	N/A	In Production

* Total resources, including P+P reserves, and M+I+Inf resources. The figures for the Serra do Rabo project refer to M+I+Inf resources (no information for reserves) SOURCES: 1- Vale S.A. 2024; 2 - Anglo American 2024; 3 - Usiminas 2025; 4 - ArcelorMittal 2024; 5 - Cadence Minerals, 2023; 6 - unauditaded; 7 - reported in the company's website; 8 - Samarco, 2023.

Value Chain

The iron ore extracted can be classified into three types: granulated, sinter feed and pellet feed. Pellet feed exhibits a particle size of less than 0.15 mm, whereas sinter feed ranges between 0.15 mm and 6.3 mm. These fines are agglomerated so that they can be used in steel production.

Figure 18. Comparison of processes for preparing iron inputs for metallurgy



Source: Vale

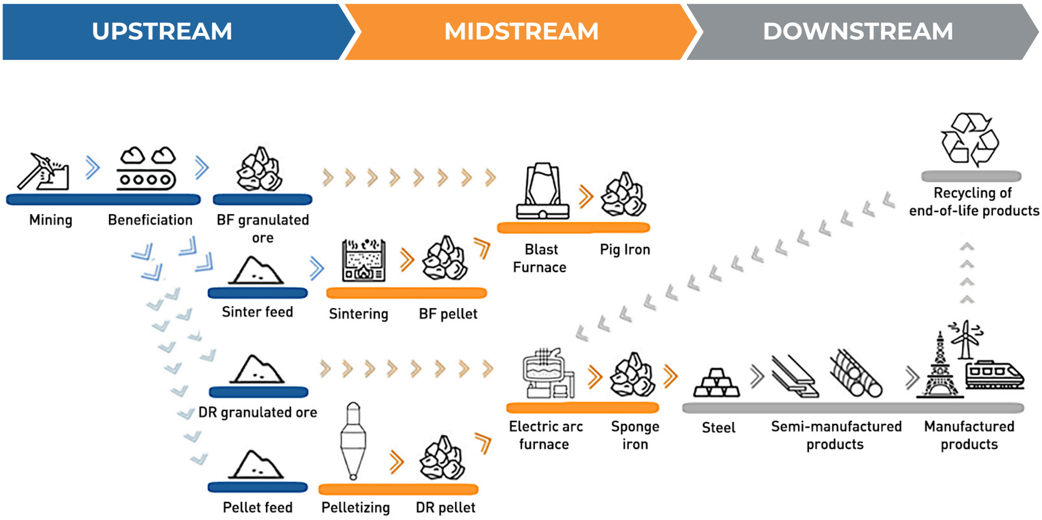
Sinter feed is processed in a sintering unit within the steelworks before it is fed into the blast furnace. Sintering is a thermal process that agglomerates fine iron ore, forming a porous charge suitable for the blast furnace. Porosity increases reactivity but reduces mechanical strength, especially in the absence of binders. Fluxes (CaO, MgO) are added to increase strength. The final sintered pellets have an iron content of 63-65% and are known as BF pellets (for blast furnace).

Both granulated ore and sintered pellets are reduced in a blast furnace to yield pig iron.

Pellet feed (< 0.15 mm) is separated after flotation or other iron ore beneficiation processes. This fraction then goes through high-intensity magnetic separation to remove impurities, resulting in a concentrated material (90% Fe_2O_3). For the aggregation of the material into pellets, a smaller amount of CaO/fluxes is added compared to sintering. The most common agglomeration process utilizes a grate furnace and operates at approximately 1,300°C. Pellets produced through this technological route are more concentrated in iron (67%) and are known as DR pellets (for direct reduction). They are inputs for the production of sponge iron through direct reduction and are fed into electric arc furnaces.

Vale has developed a technology for producing briquettes - high-quality iron ore agglomerates - through a low-temperature curing process and a technological solution that involves binders. Iron ore briquettes can be used in blast furnaces and direct reduction routes. Briquettes offer various environmental and operational advantages: up to 10% less CO_2 emissions in the steelmaking chain compared to pelletization and sintering, and also significantly lower emissions of SO_x, NO_x, and particulates. Their production process is more sustainable and efficient because it requires no water and utilizes sand derived from mining tailings.

Figure 19. Iron ore value chain



Estimation of iron content in the resource

The total iron content from the reported resources of producing deposits amounts to 21,219.55 Mt. The theoretical total iron content from producing and research-stage deposits amounts to 21,325.44 Mt. This estimation excludes process losses.

Table 19. Calculation of the total iron content in the resource

DEPOSIT	COMPANY	STATUS	RESOURCE (Mt)	GRADE (Fe) %	Fe (Mt)
(S11C and S11D)	Vale S.A.	In Production	4414.3	65.42	2887.54
Serra North	Vale S.A.	In Production	3286	65.64	2156.93
Serra East	Vale S.A.	In Production	880.8	57.98	510.69
Serra do Rabo	Vale S.A.	In Research	578.8	66.04	382.24

Mariana (Alegria, Fábrica Nova, Fazendão, Capanema)	Vale S.A.	In Production	9066.2	41.29	3743.43
Minas Centrais (Brucutu, Morro Agudo, Apolo)	Vale S.A.	In Production	4021	43.68	1756.37
Itabira (Conceição, Minas do Meio)	Vale S.A.	In Production	1498.1	45.8	686.13
Vargem Grande (Sapecado, Galinheiro, Tamanduá, Capitão do Mato, Abóboras)	Vale S.A.	In Production	8900.4	40.42	3597.54
Paraopeba (João Pereira, Segredo, Mar Azul, Capão Xavier)	Vale S.A.	In Production	5325.7	41.72	2221.88
Minas-Rio (Serra do Sapo, Itapanhoacanga)	Anglo American Minério de Ferro Brasil S.A.	In Production	5783.9	32.72	1892.49
East, Central and West Mines	Mineração Usiminas S.A.	In Production	2750	37.55	1032.63
Andrade and Serra Azul Mines	ArcelorMittal Brasil S.A.	In Production	805	43.65	351.38
Alegria Mine (Germano Complex)	Samarco Mineração S.A. (under court-supervised reorganization)	In Production	5.2 Bt	N/A	
Casa de Pedra and Engenho	CSN Mineração	In Production	6 Bt	N/A	
Tico-Tico and Ipê Mines	Mineração Morro do Ipê S.A.	In Production	N/A	N/A	
Pedra de Ferro Mine	Bahia Mineração	In Production	N/A	N/A	
Urucum and Santa Cruz Mines	LHG Mining (formerly Mineração Corumbaense Reunida S.A.)	In Production	N/A	N/A	
Pau Branco	Vallourec Tubos do Brasil Ltda	In Production	N/A	N/A	
Várzea do Lopes and Miguel Burnier	Gerdau Açominas S.A.	In Production	N/A	N/A	
Ferro + Mineração S.A.	Ferro + Mineração S.A.	In Production	N/A	N/A	
Amapá[5]	Cadence Minerals PLC	In Research	276.24	38.33	105.88
Fazenda Mocó (Ferro Verde)	Brazil Iron Mineração Ltda.	In Research	1.7 Bt	N/A	
Baratinha and Mongais	Bemisa Holding S.A.	In Research	>300	N/A	
Planalto Piauí	Bemisa Holding S.A.	In Research	>1.6 Bt	N/A	
Pedra Branca	Bemisa Holding S.A.	In Research	130	N/A	
TOTAL PRODUCTION					**21219.55**
TOTAL RESEARCH					**105.88**
GRAND TOTAL					**21325.44**

Recyclability

Steel is fully recyclable and can be reprocessed indefinitely without loss of quality. Its recycling results in significant savings in energy and raw materials. The production of steel in electric arc furnaces - which use only metal scrap - significantly reduces energy consumption compared to traditional ore-based methods. Since 1960, the energy required to produce one tonne of steel has decreased by approximately 40%.

Replaceability

Iron and steel can be replaced by several materials, both metallic and non-metallic, depending on the application. In the automotive industry, lighter materials such as aluminum and plastics are frequently used as substitutes for iron and steel. In civil construction, usual alternatives include aluminum, concrete and wood. For packaging, the main substitutes are aluminum, glass, paper and plastics.

2.8. Cobalt

Cobalt is a transition metal whose physical and chemical properties make it essential for high-tech applications. Characteristics such as high melting point (1495 °C), corrosion resistance and good magnetic properties enable its use in the production of metal superalloys applied in aviation turbines, medical implants, and high-performance industrial components (Dehaine et al., 2021). Demand for cobalt is concentrated in the rechargeable battery industry, accounting for approximately 60% of global consumption. Cobalt is an essential component of cathodes in NMC (nickel-manganese-cobalt) and LCO (lithium-cobalt oxide) batteries, which are widely used in electric vehicles, electronic devices, and energy storage systems (IEA, 2021).

In view of its importance, cobalt is listed as a strategic mineral in Resolution no. 2/2021 of Brazil's Ministry of Mines and Energy. The International Energy Agency (2021) and the International Renewable Energy Agency (2021) expect global demand for cobalt to grow by 60% to 300% by 2040, driven by the electrification of transportation and the energy transition.

Brazil's Mineral Endowment

Cobalt occurrences in Brazil are associated with three main types of deposits, in which the metal primarily appears as a byproduct of other operations:

nickel and cobalt lateritic deposits, magmatic sulfides, and manganese-cobalt deposits. Nickel-cobalt lateritic deposits (Ni-Co) are formed by the weathering of ultramafic rocks, with cobalt accumulating in the limonitic and saprolitic zones. In Niquelândia, in the state of Goiás, deposits occur over serpentinites and peridotites, with typical grades of 0.05%-0.15% Co, and are integrated with a nickel mine (ANM, 2024). Another example is in Piauí, where exploratory projects in ultramafic rocks show characteristics similar to the laterites found in Cuba (Marsh et al., 2013). The magmatic sulfide deposits located in Fortaleza de Minas, in the state of Minas Gerais, feature mineralization occurring in mafic and komatiitic rocks, with cobalt grades ranging from 0.05% to 0.08% (Almeida et al., 2007). Finally, manganese-cobalt (Mn-Co) deposits have been reported in Bahia, where manganese veins exhibit localized enrichment of cobalt and are still in the exploratory phase.

According to ANM (2024), Brazil's measured reserves of contained cobalt total approximately 1,000 tonnes. IBRAM reports (2024) that Brazil, with global reserves amounting to approximately 70,000 tonnes (data from 2017), ranks 9th worldwide, behind the Democratic Republic of Congo (DRC), Australia and Cuba, among other countries.

Main Projects and Companies in Brazil

Brazil's major cobalt deposits are shown on the map and listed in the table below:

Figure 20. Map showing the location of major cobalt deposits

Table 20. Brazil's major cobalt ore deposits

DEPOSIT	COMPANY	COMMODITIES	RESOURCE	GRADE (CO)	STATUS
Santa Rita (Fazenda Mirabela)	Atlantic Nickel	Ni, Cu, Co	281* kt[1]	0.01%[1]	In Production
Piauí Nickel	Brazilian Nickel Ltda	Ni, Co	72* Mt[3]	0.05%[3]	In Research
Jacaré	Anglo American	Ni, Co	N/A	0.19%[4]	In Research
Araguaia	Horizonte Minerals	Ni, Co, Fe, MgO, SiO_2, Al_2O_3, Cr_2O_3	N/A	N/A	In Research
Jaguar	Centaurus	Ni, Cu, Co	N/A	N/A	In Research
Fortaleza de Minas (O'Toole)	-	Ni, Cu, Co	N/A	N/A	Inactive
Niquelândia	CBA	Ni, Co	N/A	N/A	Inactive
Vermelho (V1 and V2)	Horizonte Minerals	Ni, Co, Fe^2O^3, MgO, SiO	148.8 Mt[2]	0.05%[2]	Inactive

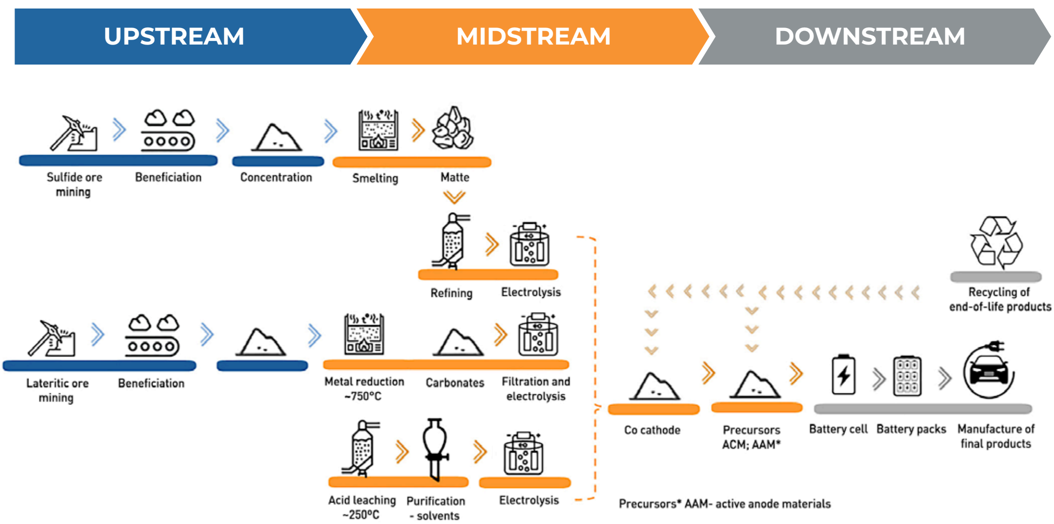
Source: 1 - Atlantic Nickel, 2022. 2 - Horizonte Minerals, 2019. 3 - Brazilian Nickel, 2021. 4 - Anglo American, 2024.
*Total resources (measured + indicated + inferred).

Value Chain

Cobalt is primarily obtained as a byproduct of nickel and copper extraction. The first step in the cobalt value chain is the concentration of the ore. The concentrated cobalt ores are refined through various processes, resulting in different forms: intermediate products (such as cobalt-containing mattes and raw cobalt hydroxide), refined metallic cobalt products (such as cathodes, briquettes, ingots, granules and powder), and refined chemical compounds (such as cobalt chloride, oxide, hydroxide and salts).

The figure below illustrates the process from cobalt extraction as a byproduct of nickel extraction to its role in the value chain of lithium-ion batteries:

Figure 21. Cobalt value chain



Estimation of cobalt content in the resource

The cobalt content from the reported resources of producing deposits amounts to 30 tonnes. The total cobalt content from producing and research-stage deposits amounts to 110.43 kt. This estimation excludes process losses.

Table 21. Calculation of the estimated cobalt content in the resource[35]

DEPOSIT	COMPANY	STATUS	COMMODITIES	RESOURCE (Mt)	GRADE (Co)%	Co (kt)
Santa Rita (Fazenda Mirabela)	Atlantic Nickel	In Production	Ni, Cu, Co	0.28	0.01	0.03
Vermelho (V1 and V2)	Horizonte Minerals	In Research	Ni, Co, Fe2O3, MgO, SiO2	148.8	0.05	74.40
Piauí Nickel	Brazilian Nickel Ltda.	In Research	Ni, Co	72	0.05	36.00
Jacaré	Anglo American	In Research	Ni, Co	N/A	0.19	
Araguaia	Horizonte Minerals	In Research	Ni, Co, Fe, MgO, SiO_2, Al_2O_3, Cr_2O_3	N/A	N/A	
Jaguar	Centaurus	In Research	Ni, Cu, Co	N/A	N/A	
Fortaleza de Minas (O'Toole)	-	Inactive	Ni, Cu, Co	N/A	N/A	
Niquelândia	CBA	Inactive	Ni, Co	N/A	N/A	
TOTAL						**110.43**

Recyclability

Theoretically, cobalt is infinitely recyclable. It is estimated that 65% of recycled cobalt comes from recycled batteries. The presence of cobalt in batteries is key, as it makes recycling economically feasible.

Replaceability

Cobalt is being replaced in various applications is response to ethical, environmental and economic concerns related to its extraction. Price volatility and the risks associated with the supply chain are contributing factors that accelerate this shift. As a result, the cobalt content in lithium-ion batteries is being gradually reduced. However, this substitution may not be feasible for certain technologies because it may compromise performance or increase costs.

The following alternative materials are notable substitutes in various sectors: barium or strontium ferrites, neodymium-iron-boron alloys, nickel-iron, cerium, manganese, various metal alloys, and ceramics. The feasibility of substitution hinges on factors such as technical performance and cost-effectiveness. It follows that even with the development of alternatives, cobalt remains a difficult element to replace in several strategic industrial applications.

35. The calculation covered the research and production phases, excluding reserves that are presently inactive.

2.9. Bauxite

Bauxite is a mineral aggregate composed of aluminum hydroxides, iron oxyhydroxides, titanium oxides, and kaolinite. It forms in lateritic deposits due to rock alteration by weathering in hot, humid regions. Bauxite's primary use is in the production of alumina, which is essential in metallurgy for manufacturing aluminum alloys. Additionally, bauxite is important for products like abrasives, ceramics and chemicals. It has other applications in the production of chemicals and cement, giving it significant economic relevance.

As a raw material for aluminum production, bauxite plays an increasingly important role in the energy transition, since aluminum alloys show both high mechanical strength and corrosion resistance. These characteristics give aluminum alloys a key role in the transportation industry, contributing to lighter vehicles and better performance. Additionally, aluminum's high electrical conductivity and malleability make it an important metal for power transmission lines, where it substitutes for copper. Aluminum is also widely used structurally in construction and in packaging, replacing steel.

Brazil's Mineral Endowment

Brazil's main occurrences of economically viable bauxite are associated with lateritic deposits created by intense weathering in regions with a hot and humid climate. The profiles in these deposits typically range in thickness from 4 to 7 meters, and their mineralogy is dominated by gibbsite - which is the preferred form of aluminum for the Bayer process.

Brazilian deposits are concentrated in two major regions: in the Eastern Amazon (Pará), where large-scale deposits are found featuring thick lateritic profiles created over sedimentary deposits. Notable deposits in this region include Porto Trombetas (MRN), Paragominas (Hydro) and Juruti (Alcoa). The other significant regions are the Southeast and Central-West (MG and GO), where residual deposits are associated with both alkaline volcanic rocks (such as in the Poços de Caldas Plateau) and altered igneous rocks. Notable mines in this region include those operated by CBA and Terra Goyana, located in the municipalities of Barro Alto and Niquelândia (GO), as well as Miraí and Itamarati de Minas (MG).

Brazil's measured and indicated bauxite reserves in Brazil total approximately 2.7 billion tonnes, according to the Geological Survey of Brazil (SGB, 2025), positioning Brazil in fourth place among the largest holders of global reserves. The deposits in Pará account for more than 90% of these reserves.

Main Projects and Companies in Brazil

The map and table below present the Brazil's major bauxite deposits:

Figure 22. Map showing the location of major bauxite deposits

Table 22. Brazil's major bauxite deposits

DEPOSIT	COMPANY	RESOURCE	GRADE (Al)	STATUS
Porto Trombetas (Oriximiná)	Mineração Rio do Norte S.A. (MRN)	600 Mt	49.5%	In Production
Juruti	Alcoa Alumínio S.A.	558.1 Mt	34.25%	In Production
Paragominas	Norsk Hydro	249.7 Mt	82.4%	In Production
Barro Alto	Terra Goyana	180 Mt	56%	In Production

Barro Alto, northern area[1]	Companhia Brasileira de Alumínio (CBA)	30.87 Mt	53.7% (Al_2O_3)	In Production
Bela Cruz	Mineração Rio do Norte S.A.	55.86 Mt	50.2%	In Production
Poços de Caldas	Alcoa Alumínio S.A.	50 Mt	46%	In Production
Itamarati de Minas (MG)	Companhia Brasileira de Alumínio (CBA)	N/A	N/A	Closed/ Exhausted
Miraí (MG)[1]	Companhia Brasileira de Alumínio (CBA)	85.09 Mt	41.89% (Al_2O_3)	In Production
Almeirim	MSL Minerals S.A.	46 Mt	57.4%	Closed/ Exhausted

Source: SGB, 2025. 1 - CBA, 2021.

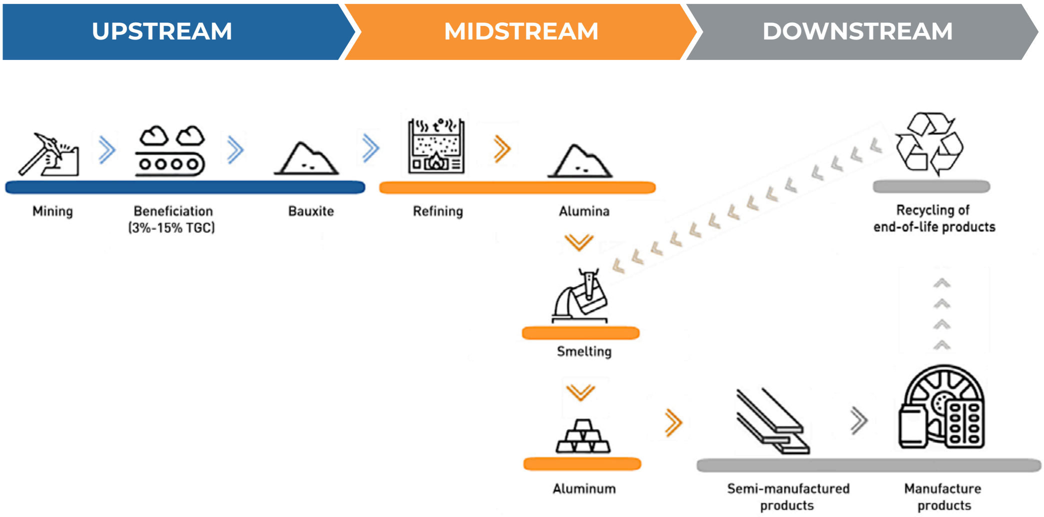
Value Chain

The aluminum value chain begins with the extraction of bauxite, the main ore used in its production. The mined bauxite is crushed, washed, dried and refined through the Bayer process. This method converts bauxite into alumina (aluminum oxide), an intermediate compound with wide industrial applications.

The alumina produced in the refining process is utilized not only as a raw material for metallic aluminum production, but is also crucial across several other sectors, including for refractory materials, water treatment, and the manufacture of abrasive and polishing compounds. Alumina can be used as a flame retardant and in other specialized applications such as the manufacture of spark plugs and other components.

Alumina is processed into metallic aluminum through an electrolytic process known as Hall-Héroult. In this stage, the calcined alumina undergoes electrolytic reduction in specific high-temperature cells. This process consumes large amounts of electricity and requires, on average, about two tonnes of alumina to produce one tonne of primary aluminum.

Figure 23. Aluminum value chain



Estimation of aluminum content in the resource

On average, 4 tonnes of dry bauxite are required to produce 2 tonnes of alumina, which in turn yields 1 tonne of aluminum (USGS, 2025). The grades indicated for each deposit were considered to calculate the theoretical aluminum supply. Based on these figures, the total potential aluminum production from the reported resources of producing deposits is estimated at 898 Mt of alumina, corresponding to 475.1 Mt of aluminum.

Table 23. Calculation of the estimated total potential alumina and aluminum production

DEPOSIT	COMPANY	STATUS	RESOURCE (MT)	GRADE (AL_2O_3)	ALUMINA (AL_2O_3) (MT)	ALUMINUM (MT)
Porto Trombetas (Oriximiná)	Mineração Rio do Norte S.A.	In Production	600	49.5%	297.0	157.2
Juruti	Alcoa Alumínio S.A.	In Production	558.1	34.3%	191.1	101.2
Paragominas	Norsk Hydro	In Production	249.7	82.4%	205.8	108.9
Barro Alto	Companhia Brasileira de Alumínio	In Production	30.87	53.7%	16.6	8.8

Barro Alto	Terra Goyana	In Production	180	56.0%	100.8	53.4
Bela Cruz	Mineração Rio do Norte S.A.	In Production	55.86	50.2%	28.0	14.8
Poços de Caldas	Alcoa Alumínio S.A.	In Production	50	46.0%	23.0	12.2
Miraí (MG)1	Companhia Brasileira de Alumínio (CBA)	In Production	85.09	41.9%	35.6	18.9
TOTAL			**1809.82**		**898.0**	**475.4**

Recyclability

Aluminum is one of the most recycled metals because it can be recycled indefinitely without losing its essential properties. More than 90% of the aluminum used in the automotive industry and in civil construction comes from recycling, which promotes the implementation of a circular model of production and consumption.

The production of secondary aluminum requires about 95% less energy than production from ore, resulting in a significant reduction in carbon emissions, as well as lower costs for businesses and consumers. Brazil is a global leader in aluminum recycling. In 2022, Brazil recycled 100% of the aluminum beverage cans sold, corresponding to 390,200 tonnes of aluminum.

Replaceability

In applications within the aerospace and automotive sectors, aluminum can be replaced by materials such as composites, magnesium, steel or titanium, depending on performance, weight and strength requirements. Aluminum and copper are often interchangeable in electrical and heat transfer applications, despite their differences in conductivity and cost.

Although the transformation of bauxite into metallic aluminum is very energy-intensive, aluminum remains widely used because of its properties: lightness, corrosion resistance, good thermal and electrical conductivity, and high recyclability.

Value chain maturity

Despite its significant geological potential and robust mining infrastructure, Brazil faces considerable challenges in advancing the processing and vertical integration of its minerals, particularly critical ones. This is a consequence of the technological maturity and concentration of key stages of the supply chain in other countries. This gap in the supply chain reflects key indicators such as the creation of higher-skill jobs, the development of new technologies, and the capture of added value throughout the chain. Technological maturity in certain areas of critical mineral processing is a limiting factor that can only be overcome through investments in research, development and innovation. The challenge for Brazil lies in building a complete production chain, including beneficiation, processing and the manufacturing of higher value-added products. These issues will be addressed in further detail in chapters 5 and 6 in this report.

3.

Demand for minerals in Brazil's path toward climate neutrality

3.1. Overview of Global and Domestic Demand for Critical and Strategic Minerals

The IEA expects global demand for minerals to triple by 2030 and quadruple by 2040, under scenarios aligned with the net-zero emissions target for 2050. According to the IEA, global demand for lithium grew by approximately 30% in 2024, while nickel, cobalt, graphite and rare earth elements saw growth ranging from 6% to 8%, driven primarily by applications in the clean energy sector (electric vehicles, storage, and grids).[36] The same report estimates that the combined market for these minerals in 2024 had already surpassed 325 billion dollars, which may more than double by 2040 under the NZE (Net Zero Emissions) scenario.

However, this disruptive growth will not occur in an environment of homogeneous supply: mineral supply chains are highly concentrated, particularly in refining and processing, which increases vulnerability to geopolitical and logistical shocks. According to the IEA, in 2024, the top three refining countries accounted for, on average, 86% of the processing capacity for copper, lithium, nickel, cobalt, graphite and rare earth elements. This percentage is higher than the 82% observed in 2020. The dependence on a

36. IEA, Global Critical Minerals Outlook 2025.

few links in the supply chain poses significant risks to the mineral security of nations that are starting or intensifying green industrialization processes.

In this global scenario, Brazil possesses unique characteristics and advantages that position it both as an emerging consumer and a potential strategic player in the CSM market. Brazil holds some of the world's largest reserves of minerals such as niobium, graphite and rare earths, and is developing promising projects for lithium and other elements (e.g., projects in the "Lithium Valley" region in Minas Gerais). The major challenge lies in crafting a strategy for these minerals that integrates mining, beneficiation and technology, in order to reduce external vulnerabilities and capture more value domestically.

Examining Brazil's demand for CSM is essential in the current global scenario of rapidly accelerating demand and highly concentrated supply. Section 3 will project this demand for 2025–2050, considering both the expansion of low-carbon technological infrastructure and the replacement of equipment reaching the end of its operating life. This exercise seeks to inform Brazil's mineral and industrial policies and to enhance Brazil's strategic positioning within the global energy transition.

3.2. Assumptions and Methodological Approach

Brazil's demand for critical and strategic minerals (CSM) was estimated using an integrated approach that combines energy planning, economic modeling, and technological analysis, taking as reference the mitigation and adaptation commitments set out in the Nationally Determined Contribution (NDC) and in Brazil's climate neutrality target for 2050. Recognizing that Brazil's energy transition will require new production chains based on low-carbon technologies, this approach focuses on the profound transformations needed in mineral-intensive sectors like power, transportation, industry and agriculture.

The modeling exercise follows the reference net-emissions neutrality scenario adopted under the Energy Transition Program (PTE2), in which Brazil achieves net-zero greenhouse gas (GHG) emissions by mid-century (see appendix A). The model employed seeks to optimize Brazil's energy and agricultural system by finding the minimum-cost configuration that simultaneously:

(i) meets the demand for energy services and agricultural products;

(ii) complies with NDC climate targets; and

(iii) endogenously selects mitigation technologies.

Based on this framework, the model selected multiple technology routes that are capable of reducing emissions while simultaneously supporting projected economic and demographic growth. The routes selected represent critical technology converters to achieve neutrality. They encompass key drivers for the electrification and decarbonization of the economy, including, but not limited to, power-generation systems (wind, solar and nuclear), stationary energy storage, electric motors, vehicle batteries, and fuel-cell systems.

The demand for CSM was estimated through a qualitative and quantitative analysis taking into account the technical, economic and environmental aspects of the main technology families within each route. The model subsequently verified the feasibility of each technology and identified its underlying material requirements. This included strategically important Brazilian metals and minerals such as lithium, nickel, cobalt, graphite, copper and rare earths.

The technological expansion pathway projected through 2050 combines the deployment of mature and economically competitive solutions - such as lithium-ion batteries, silicon photovoltaic modules, and permanent magnet wind turbines - with the gradual introduction of emerging technologies, contingent upon cost reductions and the overcoming of scale and sustainability hurdles.

This approach provides the basis for estimating the total and incremental demand for critical and strategic minerals in Brazil, encompassing not only the additional stocks required for infrastructure expansion but also the replacements needed as equipment and components reach the end of their operating life. This yields a long-term perspective on how Brazil's decarbonization will shape the nation's mineral profile, carrying direct implications for mining policies, technological innovation, and supply security.

3.3. Main Technology Families Analyzed

The sections below address the core characteristics, usage trends, and expected maturity timeframe for each of the seven technology converter routes, covering generation, storage, motorization, and energy conversion systems.

Nuclear Power

Predominant technology: PWR (Pressurized Water Reactor).

Assumptions: Angra III will come online in 2030 and no additional nuclear power plants will be built until 2050.

Associated mineral demand: Enriched uranium (U3O8) solely for power generation.

Trend:

- **Short term (2025–2035):** Angra I and II in full operation, renewed efforts to complete the construction of Angra III.
- **Medium term (2035-2045):** completion of Angra III.
- **Long term (2045-2050):** Angra III in full operation, working in integration with the Angra I and II nuclear power plants.

Stationary Energy Storage

Technologies evaluated:

Conventional: lead-acid (Pb-acid), Ni-Cd, NiMH, lithium-ion (Li-ion), NaS, NaNiCl2, Na-ion.

Flow: VRFB (vanadium), ZnBr (zinc bromine), PSB (polybromine sulfide).

Selection criteria: energy density, charge-discharge cycle efficiency, cost per MWh, and technological maturity.

Trend:

- **Short term (2025-2030):** dominance of Li-ion batteries (more specifically LFP and high-nickel NMC), and continued presence of lead-acid batteries due to their already established role in Brazil's industrial landscape.
- **Medium term (2030-2040):** LFP batteries emerge as the dominant technology, surpassing lead-acid and high-nickel NMC batteries, in parallel to the introduction of Na-ion batteries into Brazil's stationary energy storage system.
- **Long term (2040-2050):** predominance of LFP batteries, with participation of high-nickel NMC batteries and increased presence of sodium-ion batteries.

Electric Motors

Families evaluated: brushed DC motor (BDC), induction motor (IM), permanent magnet synchronous motor (PMSM), brushless DC motor (BLDC), electrically excited synchronous motor (EESM), switched reluctance motor (SRM).

Key criteria: energy efficiency, specific torque, manufacturing cost, and reliance on rare-earth materials.

Trend:

- **Short term (2025-2030):** dominant presence of permanent magnet motors (PMSM) in urban transportation. Induction motors (IM) and switched reluctance motors (SRM) maintain a limited market share in light vehicles due to market maturity and diverse performance requirements.
- **Medium term (2030–2040):** PMSMs are the preferred technology, particularly due to their excellent performance in urban environments, further increasing reliance on rare-earth materials. Induction motors remain present in light vehicles, albeit in smaller quantities and associated with specific market niches.
- **Long term (2040–2050):** widespread adoption of PMSMs, driven by the strong presence of Chinese automakers in Brazil, increasing reliance on REE such as neodymium and dysprosium.

Batteries for Electric Vehicles

Families and generations:

Prelithium: lead-acid and Ni-MH.

Lithium (current): LCO, LMO, LTO, LFP, NMC, NCA.

Post-lithium (emerging): Na-beta, metal-ion (Na, Zn, Mg), solid state (Li-S, Li-O2), and metal-air (Zn-ar, Al-ar, Fe-ar, Mg-ar, Ca-ar, Li-ar).

Ranking criteria: energy density, cost per kWh, charging time, safety, and environmental impact.

Trend:

- **Short term (2025–2030):** the LFP technology will dominate Brazil's electric bus and truck segments throughout the timeframe of the analysis, due to its good thermal stability, longer lifespan, and lower cost. LFP batteries dominate the light vehicle market thanks to their lower cost and good safety profile. High-nickel NMC batteries are also present because of their superior energy density.
- **Medium term (2030-2040):** reduced share of high-nickel NMC batteries and advancement of LFP batteries, driven by competitive costs and greater penetration of Chinese vehicles in the Brazilian market.
- **Long term (2040-2050):** continued dominance of LFP batteries for buses, cars and trucks. Technological duopoly in the light commercial vehicle market, with the coexistence of LFP and high-nickel NMC batteries.

Fuel Cells

Technologies analyzed: alkaline fuel cell (AFC), anion exchange membrane fuel cell (AEMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC).

Criteria: electrical efficiency, operating temperature, service life, cost, and suitability for vehicle or stationary applications.

Trend:

- **Short term (2025-2030):** initial deployment of proton exchange membrane fuel cells (PEMFC) in vehicles and portable systems, positioning them as the preferred technology.
- **Medium term (2030-2040):** Proton exchange membrane fuel cells (PEMFC) gain dominance thanks to their low operating temperature, high power density, good stability and longer lifespan.
- **Long term (2040-2050):** Continued PEMFC preponderance because alternative technologies will not be technologically mature to gain productive scale and market share. The literature review indicates that the hurdles described in this report will not be overcome before 2050.

Wind Power

Technologies evaluated: squirrel cage induction generator (SQIG), wound rotor induction generator (WRIG), doubly fed induction generator (DFIG), permanent magnet synchronous generator (PMSG), and electrically excited synchronous generator (EESG).

Criteria: capacity factor, levelized cost of equity (LCOE), and conversion efficiency.

Trend:

- **Short term (2025-2030):** the DFIG technology remains predominant in Brazil's wind farms.
- **Medium term (2030–2040):** DFIG continues to play a significant role, with growth in PMSG turbines, facilitated by the presence of Chinese manufacturers, that have better access to permanent magnets, and by PMSG advantages such as greater fault tolerance, operational flexibility, and lower structural costs.
- **Long term (2045-2050):** DFIG and PMSG coexist in a technological duopoly.

Photovoltaic Solar Power

Families evaluated:

1st generation: monocrystalline and polycrystalline silicon.

2nd generation: thin films (CdTe, CIGS, a-Si).

3rd generation: organic cells, perovskites, and III-V multijunctions.

Criteria: efficiency, production cost, input availability, stability, and environmental impact.

Trend:

- **Short term (2025-2035):** absolute dominance of crystalline silicon, due to its industrial maturity and competitive cost.

- Medium term (2035–2045): gradual penetration of thin-film technologies (CdTe and CIGS) as they overcome efficiency challenges and reduce their levelized cost of energy (LCOE).
- Long term (2045–2050): predominance of crystalline silicon and growth of CdTe and CIGS panels, driven by the ability of these technologies to produce flexible solar panels that offer lower structural and installation costs.

Trends in Technological Maturity and Replacement

The combined analysis of technology families points to a technological duality persisting through 2050:

- **Technology maturity** - lithium-ion, crystalline silicon, PMSMs and PEMFCs will dominate the market in the short and medium term;
- **Gradual introduction of technologies**, such as Na-ion batteries, PMSG turbines, CdTe and CIGS photovoltaic modules, that require advances in R&D, recycling infrastructure and availability of critical minerals.

The prevailing routes were selected to strike a balance between maturity and innovation: leveraging proven technologies for reliability and competitiveness while remaining open to advancements that can reduce costs and boost environmental sustainability. This approach provides an integrated view of how the technological portfolio of the energy transition will impact the demand for strategic minerals, both in terms of capacity expansion and component replacement throughout the life cycle.

Analyzing the evolution of technology families in key sectors of the energy transition up to 2050 reveals a clear trend toward the continued prevalence of mature technologies, while emerging solutions face economic, technological and scaling hurdles.

Technological progress leading up to 2050 will be characterized by the continued dominance of mature technologies alongside the selective introduction of innovations, provided that economic, environmental and production scale hurdles are overcome.

Conclusions regarding each technological route analyzed:

1. **Nuclear:** Brazil's nuclear power plants are not expected to undergo major technological changes, as no non-PWR facilities are planned;

2. **Stationary Storage:** lithium-ion batteries remain the primary focus for the Brazilian market, largely because of their superior technical characteristics. However, alternative technologies such as lead-acid and Na-ion are emerging as complementary options.

3. **Electric Motors:** While dependence on rare earth elements remains a concern, the superior performance of permanent magnet motors (PMSM) and their global market penetration suggest they will maintain their leading position throughout the period analyzed, especially in urban applications in Brazil.

4. **Vehicle Power Storage:** LFP and NMC batteries are expected to continue dominating both the global and domestic markets, with increasing emphasis on LFP due to its economic competitiveness and synergy with the growing penetration of Chinese vehicles.

5. **Fuel Cells:** PCMTP predominance is likely to continue until 2050, given their greater technological maturity compared to other alternatives still under development.

6. **Wind Power:** DFIGs continue to predominate in the short term, but the commencement of local manufacturing of PMSG turbines, coupled with the drive for greater scale and efficiency, is expected to create a duopoly in the medium to long term.

7. **Solar Power:** Crystalline silicon modules will remain the dominant technology until 2050, supported by their maturity and competitiveness. Nonetheless, thin-film technologies (CdTe and CIGS) are expected to gradually expand starting in 2040, as they overcome challenges related to critical materials and efficiency. Meanwhile, more disruptive technologies such as perovskites and multijunction cells are likely to remain limited to niche markets or pre-commercial development within the timeframe considered.

Table 24: Technology trends identified

Technologies	Technology families selected		
	Short Term	**Medium Term**	**Long Term**
Nuclear	PWR	PWR	PWR
Stationary Storage	Pb-acid; Li-ion	Li-ion	Li-ion; Na-ion
Vehicle Power Storage	Li-ion (NMC and LFP)	Li-ion (NMC and LFP)	Li-ion (NMC and LFP)
Fuel Cells	Proton Exchange Fuel Cells	Proton Exchange Fuel Cells	Proton Exchange Fuel Cells
Electric Motors	PMSM; IM; SRM	PMSM; IM	PMSM
Wind Turbine Generators	DFIG	PMSG; DFIG	PMSG; DFIG
Photovoltaic Panels	Crystalline silicon	Crystalline silicon; CdTe	Crystalline silicon; CdTe; CIGS

3.4. Estimated Demand for Materials

3.4.1. Methodological Approach and Definition of Material Intensity

The total demand for materials associated with Brazil's energy transition for 2025–2050 was estimated by combining the technology deployment projections from the energy model with the material intensities specific to each technology family.

Material intensity (MI) is defined as the quantity of a specific material (kg or t) required to obtain a unit of installed technological capacity, whether for power generation (MW) or energy storage (MWh). It is, therefore, an indicator of the mineral content embedded in each technology converter, reflecting each solution's technological stage, material efficiency, and production maturity.

The estimate covers both new capacity additions and capacity replacements - i.e., the materials needed to replace equipment that reaches the end of its operating life, based on specific average durability rates for each technology. The material intensities used in this report can be found in Appendix B.

3.4.2. Materials by Technology Family

The following sections provide a detailed overview of the major material intensities considered for the technologies selected by the energy model, as well as their trends up to 2050.

Wind Power

Major materials: copper and rare earth elements - for example: neodymium, praseodymium and dysprosium - in PMSGs.

Trends: Progressive reduction in structural mass per unit of power.

Photovoltaic Solar Power

Major materials: silicon, silver, indium, gallium, copper, selenium, cadmium and tellurium.

Trends: Greater demand for indium, gallium, cadmium and tellurium due to the growing participation of CdTe and CIGS after 2035.

Stationary Energy Storage

Major materials: lithium, nickel, manganese, cobalt, graphite and copper.

Trends:

- Lower cobalt and nickel content in newer equipment generations (LFP, Na-ion);
- Increased use of abundant materials (iron and sodium).

Vehicle Batteries

Major materials: lithium, nickel, iron, manganese, cobalt, copper and graphite.

Trends:

- Reduced share of cobalt due to NMC's smaller market share in vehicle batteries;

- Increased penetration of LFP batteries with lower critical content.

Electric Motors

Major materials: electrical steel, copper and permanent magnets (REE).

Trends:

- Increased demand for rare earths due to the growing use of PMSMs at the expense of SRMs and IMs;
- Reduction in the structural weight of vehicles due to the use of more modern metal alloys;
- Greater penetration of electric motors.

Fuel Cells

Major materials: platinum[37].

Trends:

- Extended operational durability (>20,000 hours);
- Introduction of advanced catalysts.

Nuclear Power

Major material: enriched uranium (U_3O_8).

Trends:

- Efficiency gains in fuel use;
- Expansion of the waste reprocessing and reuse cycle.

37. While the model assumes fuel cell converter units are primarily composed of platinum, PFSA and carbon black, only the demand for platinum creates a significant constraint in the overall material estimation.

3.4.3. Projected Demand for Materials (2025-2050)

The domestic demand for CSM required by key energy transition converters between 2025 and 2050 aligns with Brazil's NDC and climate neutrality target.[38] This projection was calculated using expected technological advancements and adjusted material intensities. The most significant results are described below:

- **Lithium** - demand is expected to balloon from just over 1,000 tonnes in 2025 to 37,200 tonnes in 2045. The 2025-2050 cumulative demand for lithium associated with battery-related converters is estimated at 133,000 tonnes.

- **Graphite** - the demand for graphite stands out as one of the fastest-growing, surging from 13,900 tonnes in 2025 to 446,000 tonnes in 2045. The 2025-2050 cumulative demand for graphite associated with battery-related converters is estimated at 1.6 million tonnes.

- **Copper** - the demand for copper is driven not only by its application in batteries, which accounts for 75% of the cumulative total, but also by its use in wind turbines and, mainly, electric motors. Total demand is expected to be 8,200 tonnes in 2025, increasing to 255,600 tonnes in 2045 and adding to a cumulative total of 893,900 tonnes over the entire period.

- **Cobalt** - demand is again concentrated in battery applications (95% of total demand), and is projected to remain under 1,000 tonnes until 2035, thereafter growing at a faster pace to reach 4,700 tonnes in 2045. The 2025-2050 cumulative demand for cobalt is estimated at 17,400 tonnes.

- **Nickel** - demand is once again driven almost exclusively by battery applications (99.2% of total demand), and is projected to increase from 1,400 tonnes in 2025 to ~32,000 tonnes in 2045, with most of this growth occurring after 2035. The 2025-2050 cumulative demand for nickel is estimated at 117,200 tonnes.

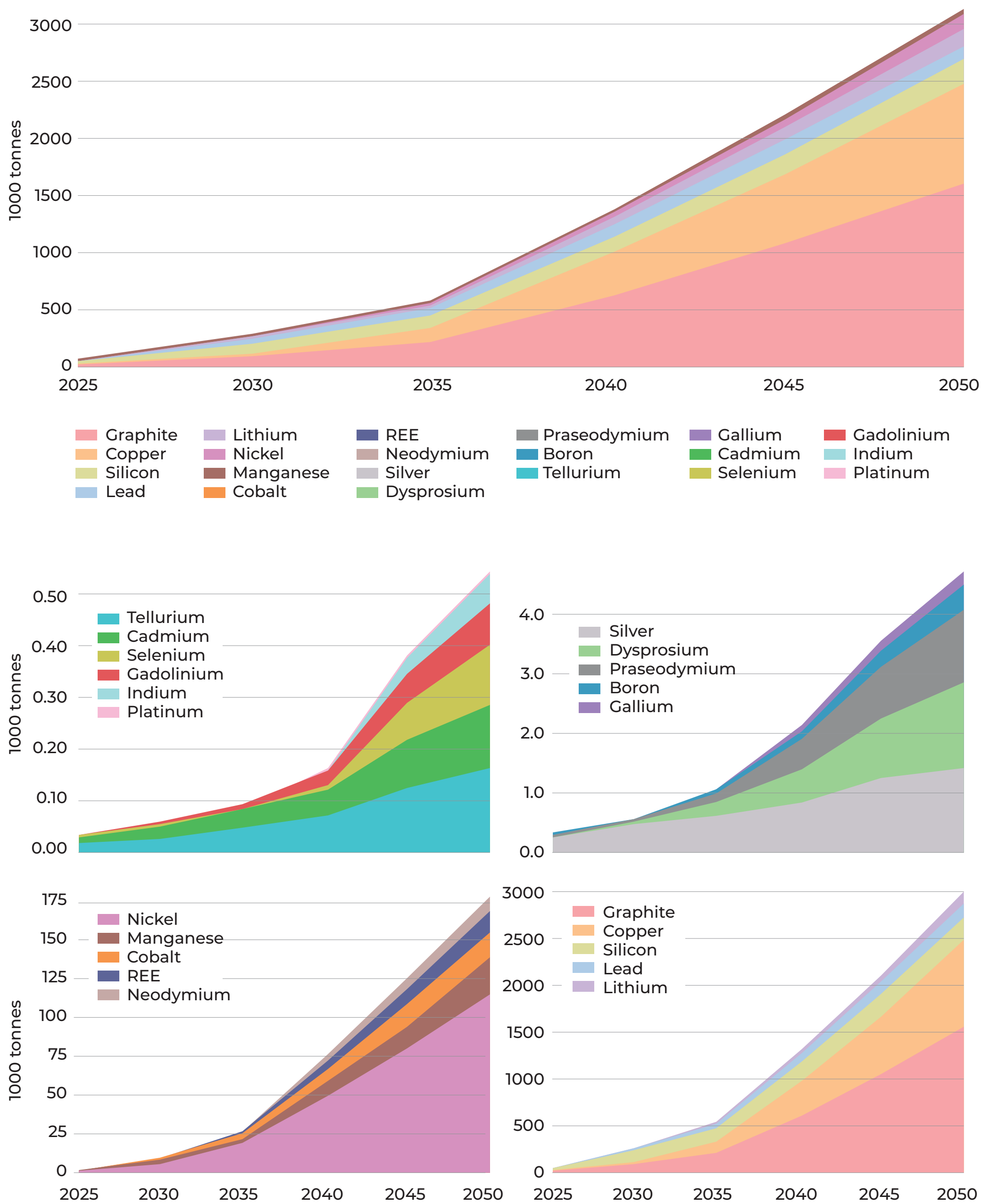
- **Rare earths** - the study focused on praseodymium, neodymium, dysprosium and gadolinium. The volumes involved are much smaller when compared to other minerals. Neodymium is the most significant element in terms of tonnage, representing almost 80% of total cumulative demand for these rare earth elements. These elements are used in the manufacture of wind turbines and electric motors. The total demand for

38. This increase in demand stems from the broader use of low-carbon technologies and excludes other uses of the relevant materials.

these elements is expected to reach a mere ~70 tonnes late in this decade, surging to 4,300 tonnes by 2045. The 2025-2050 cumulative demand is estimated at 12,800 tonnes.

- **Uranium** - the demand for this mineral is geared toward meeting the anticipated needs of nuclear power generation. The demand estimated for 2025 (446 tonnes) is projected to grow at a fast clip until 2040 and then to level off, remaining stable at 910 tonnes in 2040-2050. The 2025-2050 cumulative demand for uranium for nuclear power generation is estimated at 4,700 tonnes.

Figure 24. Cumulative demand for materials during the analysis period, with materials grouped together (top) and separated by order of magnitude (bottom)



Source: Prepared by the authors (2025).

These trends shape a materials-intensive transition scenario, particularly after 2035[39], as Brazil's goal of achieving net-zero greenhouse gas (GHG) emissions drives a rapid shift to low-carbon technologies.

This sudden increase may cause a mismatch between supply and demand, potentially creating bottlenecks in production chains. Technological advancements, combined with recycling and design innovations, will play a crucial role in reducing pressure on the supply of critical minerals and supporting Brazil's mineral and industrial self-sufficiency.

39. Prior to 2035, the majority of GHG emission reductions will come from transformations in the AFOLU sector, as discussed in PTE 2 (see Appendix A). This allows a more gradual adoption of high-cost solutions, such as the widespread deployment of electric vehicles, stationary batteries, and renewable energy sources.

4.

Key aspects of the comparative analysis of supply and demand for critical and strategic minerals in Brazil

The analyses of strategic mineral supply and demand were conducted independently and in parallel, each with its own objectives, methodologies and sources of information tailored to its specific scope. The assessment of demand focused on minerals that are significant to energy conversion and storage technologies, whereas the analysis of supply primarily drew on Brazil's mineral endowment, examining minerals that critical and strategic for the energy transition and their potential availability for extraction. In result of these differences in methodology and analytical perspective, the lists of minerals analyzed in each study are not identical, although they show significant overlap in some cases. This divergence does not undermine the consistency of the results, but rather underscores the complementary nature of the approaches used to provide an integrated representation of the challenges and opportunities associated with Brazil's energy transition.

An important aspect facilitating the comparative analysis for certain minerals was that both the supply and demand data surveys were conducted in "net" terms, meaning that the volumes calculated already correspond to the "pure" mineral (available for, and/or actually consumed in, the converters). As is known, the extraction of the minerals addressed in this report requires processing large quantities of raw materials, much greater in mass than the specific quantity of the mineral itself, because of the presence of rocks and other impurities.

Regarding supply, the analysis considered information on Brazil's raw mineral resources, estimated mineral content, reserves, and latest annual production figures (2024), as presented in the sections below. The mineral supply estimates in this report were based primarily on resource data, bearing in mind that only a fraction of this potential is actually converted into economically viable reserves. These estimates exclude losses incurred during mineral beneficiation and processing, and reflect only the "in situ" grades of currently known resources.

Demand-side figures are net quantities that correspond only to the energy use of the converters and exclude other potential applications. Our analysis therefore does not address the total demand for minerals, but rather the portion most directly associated with the energy transition.

Each research institution built its own analytical framework based on Brazil's list of strategic minerals. It follows that the lists of minerals whose supply and demand were examined vary, reflecting each institution's distinct approach. The list below shows the minerals selected by each institution, highlighting the overlaps:

Table 25: List of Minerals including Supply and Demand Studies

COPPE List	In common	CETEM List
Lead	Praseodymium	Niobium
Silver	Dysprosium	Iron
	Gadolinium	
Silica	Copper	Bauxite (Aluminum)
Boron	Neodímio	-
Cadmium	Lithium	-
Tellurium	Graphite	-
Selenium	Cobalt	-
Gallium	Nickel	-
Indium	-	-
Platinum	-	-
Manganese	-	-

Rare earth elements (REE) are a group of 17 chemical elements that share similar physical and chemical properties and are typically found together in specific minerals. The proportion of each element in rare earth oxides varies according to the geological composition of each deposit. Although Brazil holds the world's second largest REE reserve, publicly available data on the individual distribution of these elements remain limited.

Current REE information in Brazil primarily refers to total mixed oxide grades, which represent the material presently being produced and exported. Detailed data on the grade of specific elements such as neodymium (Nd), praseodymium (Pr) and dysprosium (Dy) are not available for Brazilian deposits.

This limitation stems mainly from the still incipient stage of domestic production and the lack of in-depth geological studies focused on the composition of the deposits. The data on geological resources and reserves now available refer to their total REE content, providing no details on the individual elements they comprise. As a result, there is no consolidated or sufficiently detailed public information on the content of strategic elements in Brazilian deposits.

This makes it impossible to accurately estimate the potential supply against the projected demand for specific rare earth elements.

A comparative analysis between supply and demand data was possible for the following minerals: copper, graphite, lithium, nickel and cobalt.

The table below provides all available information on the supply and demand of critical and strategic minerals in Brazil:

Table 26: Supply and demand estimates for critical and strategic minerals in Brazil

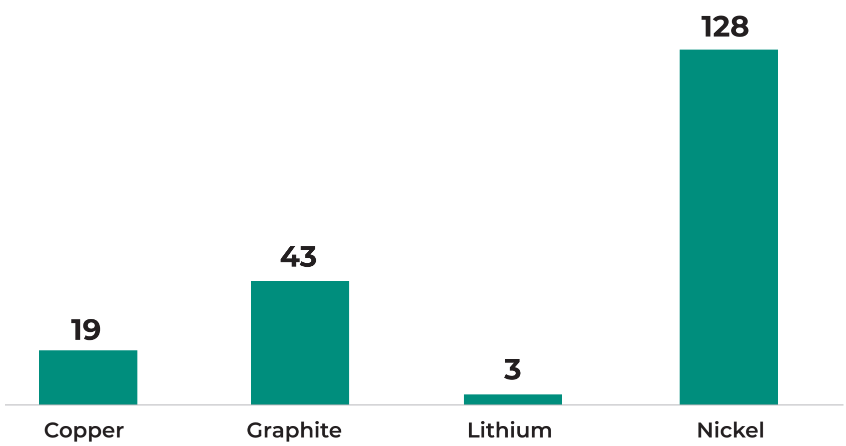
	SUPPLY				DEMAND	
Mineral	**Gross Resource[40] (Kt)**	**Content (Kt)**	**Reserve 2024 (Kt)[41]**	**Production 2024 (Kt)[2]**	**Use**	**Kt**
Copper	6,360,370	35,730	17,000	527[42]	Batteries	684
					Wind Power	60
					Solar Power	0
					Electric Motors	141
					Total	**894**
Graphite	698,330	105,350[43]	74,000	68	Batteries	1,600
					Total	**1,600**
Lithium	151,260	740	390[44]	10	Batteries	133
					Total	**133**
Nickel	2,020,387	12,770	16,000	77	Batteries	116
					Wind Power	0
					Electric Motors	1
					Total	**117**
Cobalt	221,080	110	N/D[45]	N/D	Batteries	16
					Wind Power	0
					Electric Motors	1
					Total	**17**
REE	4,058,100	6,301	21,000	0.020	N/A	N/A
Neodymium	N/A	N/A	N/A	N/A	Wind Power	2
					Electric Motors	8
					Total	**10**
Dysprosium	N/A	N/A	N/A	N/A	Wind Power	0
					Electric Motors	1
					Total	**1**
Praseodymium	N/A	N/A	N/A	N/A	Wind Power	0
					Electric Motors	1
					Total	**1.22**
Gadolinium	N/A	N/A	N/A	N/A	Wind Power	0
					Electric Motors	1
					Total	**0.08**

40. Gross Mineral Resource - mineral of interest + gangue (rocks and impurities).
41. USGS Mineral Commodity Summary 2025 - https://pubs.usgs.gov/periodicals/mcs2025/mcs2025.pdf
42. Copper content.
43. Total graphitic carbon.
44. The up-to-date estimate for lithium reserves stands at 1,370,000 tonnes (MME).
45. N/A - not available.

As the table shows, the mass of raw ore required differs significantly from the mass of specific minerals contained in the materials mined. The figures also indicate that the conversion of a mineral's specific raw resource into actual reserves is not straightforward. Mineral resources will not turn into mineral reserves if that conversion is not shown to be technically and economically feasible, taking into account modifyer factors like mining, processing, infrastructure, production costs, market conditions (demand and price), and environmental and social aspects. Resources deemed measured and indicated can be converted, respectively, into proven and probable reserves only after this detailed analysis. Furthermore, the advancement of mineral production and processing depends not only on the availability of reserves, but also on the inputs, technologies, and machinery necessary to make the operation viable.

The comparison in the graph below between current reserve levels and cumulative demands (2025-2050) clearly shows that Brazil has the theoretical capability to supply its domestic needs while partially satisfying global demand. To do so, Brazil must strengthen its competitive positioning within global value chains by developing its ability to deliver quality, high-value-added products at market-competitive prices.

Figure 25: Relationship between current reserves and cumulative demand until 2050



Source: Prepared by the authors based on project data.

It was not possible to create this indicator for cobalt because of the lack of available data on reserve volumes and production.

Within this subgroup of critical and strategic minerals, nickel is undoubtedly the most prominent, boasting reserves that exceed the amount needed to meet the energy demands of economic sectors by more than 128 times. Copper and graphite also show very significant ratios, respectively 19x and 43x.

Lithium is the only mineral whose reserve volume does not exceed the cumulative demand for energy purposes by so comfortable a margin. However, the MME has recently published updated figures, raising lithium reserves to 1.37 million tonnes. If confirmed, this new estimate places reserves at more than ten times the aforementioned cumulative demand.

Notwithstanding their large reserves, the production levels of these minerals are still low. Considering that a significant portion of current production is directed toward non-energy uses, new investments in the extraction of these minerals will be necessary so that domestic production can satisfy the demand for converters.

In summary, the analysis makes it clear that there are no restrictions on the mineral endowment side. Brazil has the capacity to not only meet its own mineral demand but also to become a major global supplier of these minerals, as demand grows rapidly in the coming decades. However, transforming these reserves into actual production will depend on government and non-government efforts to develop the sector in Brazil.

This study also projects a growing demand for energy converters (batteries, electric motors, wind turbines, solar panels, etc.), whose manufacture will require critical and strategic minerals. Because converter-related demand is met primarily through imports, Brazil faces a technological and industrial dependence that restricts its autonomy in this strategic sector. Brazil can use the resolution of these two issues - leveraging its significant CSM reserves and plugging the technological product gap - as a springboard to bolster domestic production chains, generate income, and create jobs. This will be especially important for the main minerals required to manufacture of these converters: lithium, nickel, cobalt, copper, graphite and rare earths.

The simple fact that a nation boasts a rich mineral endowment does not automatically guarantee it will become a significant player on the global mineral stage. Only by intelligently and strategically using these resources and strengthening production and industrial chains can Brazil transform its geological potential into a competitive edge, mineral sovereignty, and technological leadership. Brazil has the potential to evolve from a nation with significant geological endowments into one with a well-structured mineral sector that adds value to its production chains, boosts the mineral and metallurgical industry, and plays a leading role in the global energy transition (IBRAM, 2025).[46]

Even so, it is crucial to note that the interplay between mineral supply and demand takes place within a globally interconnected chain, where extraction, processing and technological activities often occur in different countries. Brazil's domestic mineral supply alone is not enough to ensure access to these technologies, making integration into global supply chains essential. Recycled end-of-life products can also become a significant domestic source, especially for minerals like lithium, enhancing material security and supporting the sustainability of Brazil's production cycle.

Brazil needs to identify which strategic value chains - energy converters, critical minerals, and clean technologies among them - to prioritize for investment so as to can bolster its international position, mitigate external vulnerabilities, and ensure autonomy and sustainability amid growing global demand for minerals and the shift to a low-carbon economy.

46. IBRAM, 2025a: https://ibram.org.br/wp-content/uploads/2025/05/IBRAM_news_green-paper_2025_web.pdf

5.

Main barriers and challenges to production

With its extensive geological resources and strong mining tradition, Brazil has the potential to take a leading role in the energy transition and in the production of advanced technologies. Yet a significant gap remains between the nation's geological potential and productive and technological capabilities.

Brazil's mining sector faces structural and institutional challenges that constrain its competitiveness and impede the economic use of its resources. These challenges include: inadequate industrial infrastructure, high logistics costs, a bureaucratic and complex tax system, limited access to funding and skilled labor, and poor integration between science, technology and industry. These limitations hinder the development of beneficiation activities and the vertical integration of production, leaving Brazil primarily as an exporter of low-value-added mineral products.

Despite these challenges, some opportunities are emerging for Brazil to integrate into global value chains - both by diversifying its production base and by meeting the domestic and international demand for strategic minerals. The sections below cover the regulatory framework, the main limitations to research, exploration and processing, and the opportunities for Brazil to competitively integrate into targeted supply chains.

5.1. Current legal framework

The regulatory framework of Brazil's mineral sector is undergoing continuous adaptation in response to the evolving dynamics of the global economy and the increasing demand for critical minerals spurred by the energy transition. Brazil's mineral governance is taking on a strategic role, necessitating coordinated efforts across the industrial, environmental, technological and innovation sectors.

The sector's regulatory framework centers on the Mining Code (Decree-Law no. 227/1967, as regulated by Decree no. 9,406/2018) and is supervised by the National Mining Agency (ANM), established under Law no. 13,575/2017. These instruments set out the fundamental rules for research and extraction activities and supervision of mineral operations. The framework is complemented by long-term plans, such as the 2050 National Mining Plan (PNM 2050) and the Twenty-Year Geology, Mining and Mineral Transformation Plan (2010-2030 PDGMTM), both designed by the Ministry of Mines and Energy (MME) to align the sector's productive, environmental, and technological aspects.

In recent years, Brazil has made progress in integrating mineral policy with the energy transition and reindustrialization efforts, embedding mining within its sustainable development strategy. Initiatives such as the Ecological Transformation Plan (PTE), the New Brazilian Industry Program (NIB), and the National Energy Transition Plan (PLANTE) provide guidelines for decarbonization, technological innovation, and industrial competitiveness (see table 1). By focusing on green infrastructure, clean technologies, and low-carbon production chains, these plans point to opportunities for developing integrated and sustainable mineral chains in the medium to long term.

Table 27: Policies guiding Brazil's reindustrialization process

Ecological Transformation Program - PTE	New Brazilian Industry Program - NIB	National Energy Transition Plan - PLANTE
Sustainable Financing	Agro-industrial chains	Agro-industrial chains
Technological densification	Programs	Programs
Bioeconomy	Urban quality of life	Urban quality of life
Energy transition	Digital transformation	Digital transformation
Circular Economy	Bioeconomy, decarbonization and **energy transition and security**	Bioeconomy, decarbonization and **energy transition and security**
New infrastructure and adaptation to climate change	Defense	Defense

Source: CETEM, 2025.

Despite this progress, challenges remain that hinder the modernization of the regulatory framework and limit the predictability of investments. The sluggish licensing process, the duplication of roles between federal and state agencies, and the lack of consistent tools to support value creation continue to constrain the sector's competitiveness.

The complexity of environmental and social regulations, particularly in regions like the Amazon, also calls for new institutional solutions grounded in dialog, transparency, and predictability (FGV, 2025). At the same time, Brazil must align with international standards for mineral sustainability and traceability, not only to meet growing market and investor expectations but also to facilitate the control of compliance with environmental and social regulations.

Overcoming these gaps is key to create a regulatory environment that fosters innovation and green industrialization. The effectiveness of these reforms hinges not only on new legal and economic instruments but also on cross-institutional coordination and a long-term vision that align the regulatory framework with the energy transition and Brazil's global competitiveness.

The next sections present an analysis of the main limitations affecting research, exploration, and processing, alongside a discussion of the regulatory, technological, and financial levers that can enhance mineral research, support responsible exploration, and expand processing capacity in Brazil.

5.2. Limitations to research, exploration and processing

Despite recent regulatory and institutional advances, Brazil's mining sector continues to face structural challenges that impede the transformation of its geological potential into economic value. Recent studies by IBRAM and CETEM (2024) indicate that limited access to funding, inadequate logistics and technological infrastructure, and poor integration between science, technology and industry continue to constrain the development of new mines and the vertical integration of production. These factors directly affect the research, exploration, and processing stages, which remain heavily reliant on external factors, and burdened with high costs and regulatory uncertainties.

Building on this diagnosis, this section seeks to identify the major bottlenecks that continue to hinder the expansion and modernization of Brazil's mineral production chain, and to propose strategies to boost competitiveness and support the sector's alignment with the ongoing energy and technological transition.

5.2.1 Research and exploration

The mineral research and prospecting phase in Brazil remains plagued by structural obstacles that diminish its attractiveness and constrain the discovery of new reserves. Although geological knowledge has improved in recent decades, approximately 49% of Brazil's territory is mapped at the 1:250,000 scale - suitable only for a broad overview - whereas just 27% is mapped at 1:100,000, the scale needed to pinpoint promising areas and evaluate geological risks (MME, 2022; Amaral, 2025).

Regional disparities worsen this situation. Only 37% of the Amazon region is mapped at the 1:250,000 scale and 8% at 1:100,000 (MME, 2022), while in other regions coverage at 1:100,000 reaches 55% (Amaral, 2025). This combination of cartographic voids and low-resolution mapping restricts the ability to estimate reserves and assess the true potential, particularly in hard-to-access regions. This situation stems from a history of low prioritization, alongside logistical, environmental, and institutional barriers that raise operating costs and add complexity to new surveys (Costa, 2023; Szlafsztein, 2018).

Beyond mapping constraints, insufficient funding and high exploratory risks continue to restrict the expansion of research projects. According to IBRAM and CETEM (2024), public funding for mineral research is fragmented, while private investment is discouraged by the absence of guarantees and by regulatory instability. In international comparison, countries like Australia and Canada allocate between 5% and 8% of their mineral investments to geological exploration, whereas Brazil invests less than 1%, according to the Fraser Institute and World Mining Data (2023).

Other structural bottlenecks undermine the efficiency of prospecting, for example:

- poor infrastructure for detailed geological mapping;
- shortage of skilled labor in geology, mining engineering, and geoprocessing;
- poor integration between universities, research institutes and mining companies;
- insufficient public and up-to-date geological databases.

Despite these limitations, Brazil has strong scientific and institutional capabilities[47], notably through CETEM, SGB/CPRM and federal universities

47. The potential for collaboration between science, industry, and government for mineral innovation can be gleaned from the Catalog of Mineral Technology Centers (IBRAM, 2018), listing over 70 Brazilian government and non-government entities and laboratories with substantial expertise in mining and metallurgy.

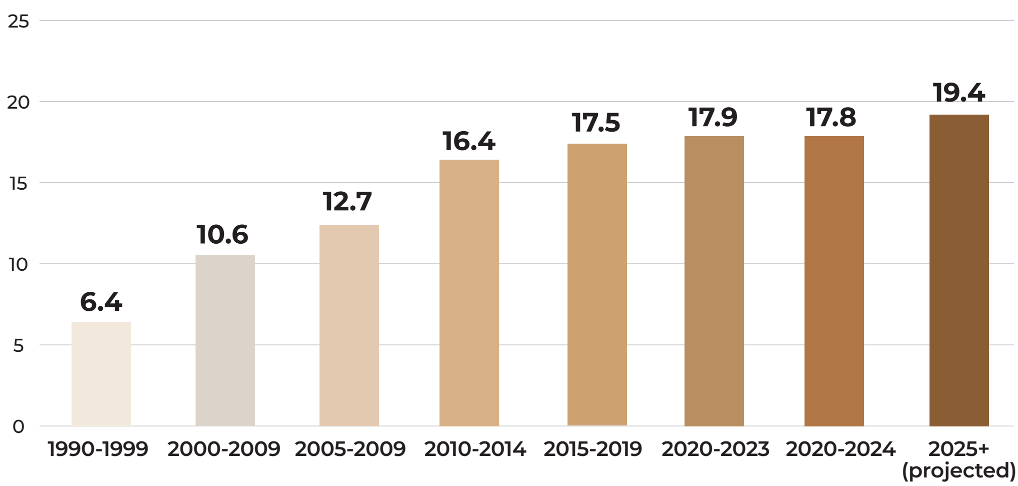
with established R&D expertise in mining engineering, energy, and industrial sustainability, such as COPPE/UFRJ. These institutions form a technical network capable of supporting applied research initiatives, particularly when coordinated around cooperative R&D programs, open data models, and international partnerships focused on mineral innovation and traceability.

5.2.2 Lead time between reserve identification and the initiation of commercial production

The lead time between the discovery of a mineral deposit and the commencement of actual mineral production is one of the primary structural bottlenecks in Brazil's mining sector, with a major impact on the availability of minerals essential for the energy and digital transition. Globally, average mine development time can reach up to 18 years, up 40% from 15 years ago. Each additional week of delay can cost tens of millions of dollars, significantly affecting the project Net Present Value (NPV) (ERM, 2025).

According to S&P Global Market Intelligence (2025), the global average time for a mine to come online has increased from 6.4 years in the 1990s to 19.4 years in 2025, reflecting the growing complexity of regulations and social and environmental requirements (Figure 26).

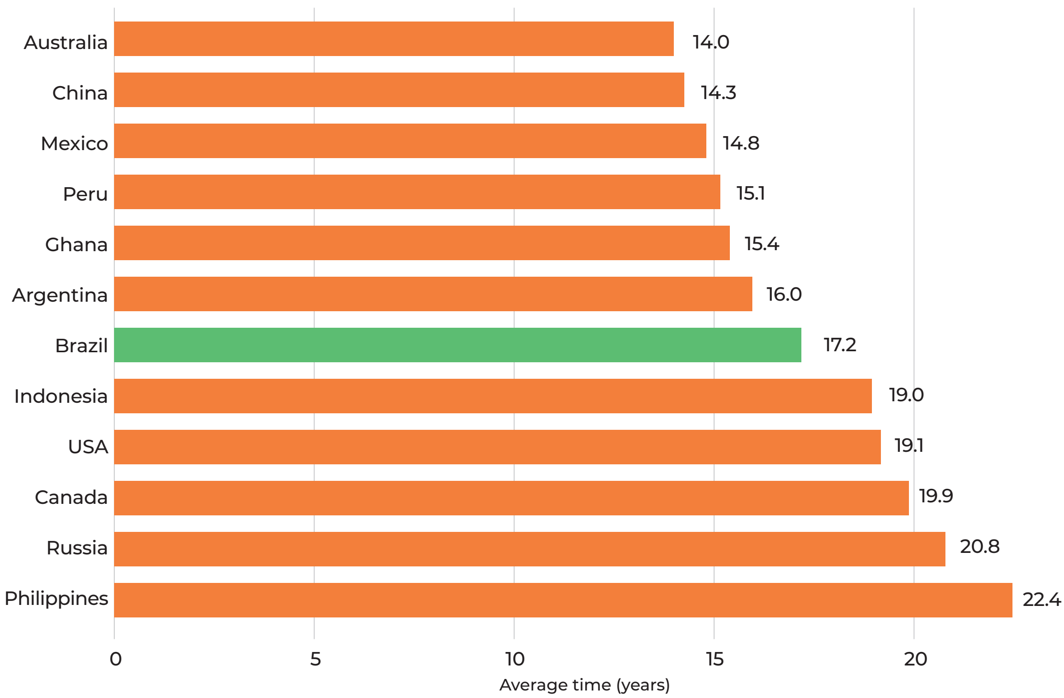
Figure 26. Change in the average time to the start of mineral production (1990-2024)



Source: S&P Global Market Intelligence, 2025

Although Brazil possesses great geological diversity and robust technical capabilities, the mine development cycle - from prospecting to commercial operation - remains marred by excessive institutional complexity and timelines exceeding the international average. The current average time between discovery and the commencement of mineral production is 17.2 years, exceeding the global average of 15.5 years (S&P Global, 2025). Brazil's longer cycle, relative to mature mining economies like Australia, China and Mexico, reflects persistent regulatory and environmental coordination challenges. These figures underscore how challenging it is to convert geological potential into actual production - and consequently, into competitiveness - in a fast-evolving energy and digital transition scenario.

Figure 27. Average time between mineral discovery and production, by country and commodity (2024)



Source: Prepared by the authors based on data from S&P Global Market Intelligence, 2025

This protracted timeframe stems from a combination of interconnected factors: increasing regulatory, social and environmental complexity; slow and fragmented environmental licensing processes; low regulatory predictability; insufficient detailed geological data; and poor coordination between government agencies and private investors.

Structural challenges in infrastructure and logistics compound these institutional constraints, especially in mineral frontier regions, such as Legal Amazonia, where environmental restrictions and geographic isolation raise costs and further delay the implementation of new projects.

In summary, the time required to bring a mine into operation in Brazil is not aligned with the pace and urgency of the ongoing energy and digital transition. Failure to advance the integration of mineral, environmental and industrial policies (without weakening environmental safeguards), may cause Brazil to miss strategic opportunities provided by the global reshaping of mineral supply chains. Nimble institutions, legal certainty and integrated sustainability will be key for Brazil to convert its geological potential into a competitive edge and global leadership in mineral production.

5.2.3 Processing and industrialization

The beneficiation, refining and industrial processing stage represents one of the most significant structural bottlenecks in Brazil's mineral supply chain. Brazil has traditionally been an exporter of raw ore, with limited capabilities for vertical integration in mineral production. This limitation reduces the sector's value creation and competitiveness, leaving it reliant on imported manufactured products made from its own minerals.

In 2023, only 5% of the lithium extracted in Brazil was processed domestically, and refined nickel accounted for under 40% of total production, according to data from MME and ANM (2024). The primary barriers are inadequate industrial infrastructure, expensive energy and chemical inputs, low-technology separation and purification routes, lack of tax and credit incentives for refining plants, and regulatory uncertainty around industrial licensing and taxation.

These technical bottlenecks occur within an economic environment defined by the so-called "Brazil Cost" - structural constraints such as a heavy tax burden, excessive bureaucracy, poor logistics, and regulatory uncertainties - that raise the cost of mineral production and reduce the attractiveness of new investments. The unpredictability of taxation and the complexity of the licensing system continue to hinder the expansion of projects and the development of a business environment more conducive to competitiveness.

In the tax sphere, Brazil's royalty system (CFEM) is based on gross revenue, with rates ranging from 1% for gold to 3% for manganese and 2% for other substance. Although comparable to models such as the Canadian or Australian ones, it lacks tools for reinvestment in production, incentives for innovation, and alignment with value-added policies.

Table 28 summarizes the mineral royalty frameworks of selected countries. Although Brazilian rates are moderate and internationally competitive, the absence of reinvestment tools and technological incentives contributes to industrial lag and a limited domestic processing.

Tabela 28. Tax burden and competitiveness in the mining sector

Country	Type of Levy	Average tax range[48]	Key Remarks
Brazil	Gross sales revenue	1% (gold), 3% (manganese), 2% (other substances)	No specific allocation for innovation or R&D
Canada	Net income (varies from province to province)	5% to 14%	Regional tax incentives and local reinvestment
Australia	Production (per tonne or equivalent percentage, depending on the state)	3% to 7% (average equivalent)	Royalties linked to reinvestment in local technology and innovation
China	Gross sales revenue	1% to 9% (iron), up to 12% (graphite)	State control and verticalization subsidies
USA	Gross revenue (varies from state to state)	2% to 12.5%	Complex but predictable and decentralized structure

Source: Prepared by the authors based on data from CETEM, 2025.

Additionally, a broader comparative analysis, presented in Table 29, illustrates how institutional and regulatory factors influence the global competitiveness of the mineral sector. Countries such as Australia, Canada and the United States stand out for the maturity of their tax mechanisms, transparency in licensing processes, political stability and administrative efficiency. Despite the high level state control, China holds a prominent position for its mineral endowment, production capacity and pricing power.

48. The ranges represent averages or equivalent royalty rates on production or revenue, according to each country's methodology..

Table 29. Comparison between Brazil and major mining countries regarding indicators of mineral sector development[49]

Development indicators	Brazil	USA	Australia	Canada	China
Tax and regulatory feasibility	Fair	High	High	High	Fair
Maturity of the tax system	Fair	Fair	High	High	Fair-low
Transparency and efficiency of licensing processes	Fair-low	High	High	High	Fair-low
Royalty payment system	Fair-low	Fair-low	High	High	Fair
Tax burden compatibility	Fair-low	Fair	Fair	High	Fair
Bureaucratic streamlining	Low	Fair-low	Fair	High	Fair
Energy security	High	Fair-low	Fair	High	Fair
Regulatory competence	Fair	Fair	High	High	Fair
Stability of mineral policy	Fair	Fair-low	High	High	High
Freedom in business relations	Fair	High	High	High	Fair-low
Maturity of environmental management	Fair	High	High	High	Fair
Contribution to global mineral production	Fair-low	Fair	Fair	Fair	Very high
Mineral tradition	Fair	Fair	High	High	High
Pricing power	Low	High	Fair	Fair	High

Very high | High | Fair | Fair-low | Low

Source: CETEM, 2025.

49. The "Very High", "High", "Fair", "Fair-Low" and "Low" categories for each indicator reflect the overall perception of the international mining sector in 2024 regarding the business and operational environment in each country. This perception is shaped by an analysis of several key factors that drive investment and mining operations. The information was compiled based on reports and research by leading organizations in the sector, including the Fraser Institute (Annual Survey of Mining Companies 2024), market analyses from Deloitte & Touche LLP (Government of Brazil Mining Sector Technical Support and Cooperation Reports) and KPMG/ICMM (International Council on Mining and Metals), data from mineral sector associations (such as IBRAM in Brazil and PDAC in Canada), as well as significant news and economic reports published during 2024. These categories represent a synthesis of the prevailing industry perspective and may vary depending on the specific source or type of mineral commodity.

Alongside internal tax and regulatory hurdles, Brazil faces structural challenges in a global landscape where the processing of critical minerals is highly concentrated in specific geographic regions. China's dominance in global value chains is reinforced by its control over roughly 80% of rare earth refining and 60% of lithium and cobalt processing (IEA, 2024), which increases the vulnerability of raw-material-exporting countries. Australia, Canada and other nations are working to reduce this dependence through programs that stimulate the midstream sector - the intermediate phase between extraction and manufacturing - through a combination of tax incentives, targeted credit lines, and technological support to expand their industrial capabilities.

Despite its significant geological advantages and scientific capability, Brazil still lacks a robust mineral industrial policy that can similarly boost competitiveness and integrate extraction, processing and technological innovation. Overcoming these challenges is key to converting geological potential into leadership in production.

The global trends reshaping mineral supply chains and the rising demand for low-carbon technologies create new strategic opportunities for Brazil.

6.

Investment and cooperation opportunities

The reshaping of global supply chains for critical and strategic minerals creates a favorable environment for Brazil to expand its activities and move into higher-value-added stages - especially beneficiation and refining. After decades in the role of primary product exporter, Brazil now has the geological, technical and institutional capabilities to compete more effectively in the midstream segment.

Brazil's prominent position is bolstered by the growing demand for inputs for the energy transition. According to SGB/MME projections (2025), supply of these minerals may fall short by 2050, particularly those that are key drivers of industrial development: graphite, copper, lithium, nickel, rare earths and iron.

Transforming this natural endowment into production and technological capabilities requires consistent industrial policies, a stable regulatory framework, and stronger integration between research and industry. The importance of transition minerals underscores the need to develop domestic supply chains capable of meeting domestic demand and positioning Brazil as a reliable and sustainable global supplier.

To this end, Brazil has at its disposal - and must continue to strengthen - the following levers:

- **Economic mechanisms and financing instruments:** the government and the private sector have created mechanisms such as investment funds and targeted credit lines, for example, the R$ 5 billion FINEP-BNDES loan, equity and grant program designed to support business plans strategic minerals processing. These initiatives will stimulate new projects, attract technology and facilitate the vertical integration of the mineral production chain.

- **Regulatory modernization and public policy strategy:** bills and strategic plans (PL 2780/24, MEL, PlanGeo) designed to streamline processes, support the sector, and enhance predictability and legal certainty. Clearer regulations can help attract investors and promote sustainability. A comprehensive and robust mineral strategy provides guidance and supports integration with industrial and development policies.

- **State government leadership in mineral governance:** Brazilian states are increasingly taking on a strategic role in the mineral agenda. Minas Gerais and Goiás lead the way with dedicated plans and agencies to promote the sector, while Amazonas, Bahia, Ceará, Pará and Rio Grande do Norte are developing regional initiatives focused on research and investment attraction. This decentralized movement, when aligned with national objectives, strengthens mineral governance, fosters sustainable development, and enhances Brazil's lead in global strategic mineral supply chains.

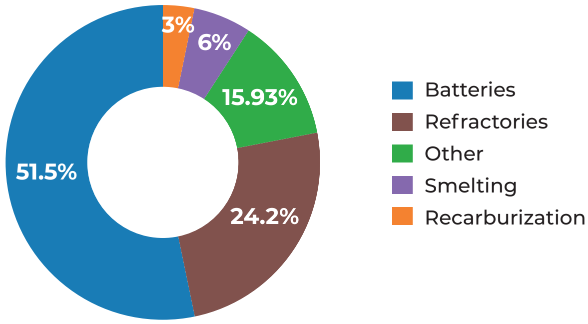
- **Regional integration and international cooperation:** Coordination with other Latin American countries can reduce inequalities, increase competitiveness, and move the region beyond a raw-material-supplier role. Integration strengthens strategic positioning in the global economy.

In light of this scenario, the subsections below address some priority minerals - selected for their importance to the energy transition and Brazil's supply potential - describing opportunities for advancement in midstream processing (beneficiation/refining) and applied R&D, in alignment with national policies and state initiatives.

6.1. Graphite

As noted earlier, graphite is a critical input for the energy transition, playing a central role in lithium-ion batteries for electric vehicles and energy storage systems. Today, batteries already account for the largest share of global graphite consumption (~51%), surpassing traditional industrial applications such as refractories and smelting (Figure below).

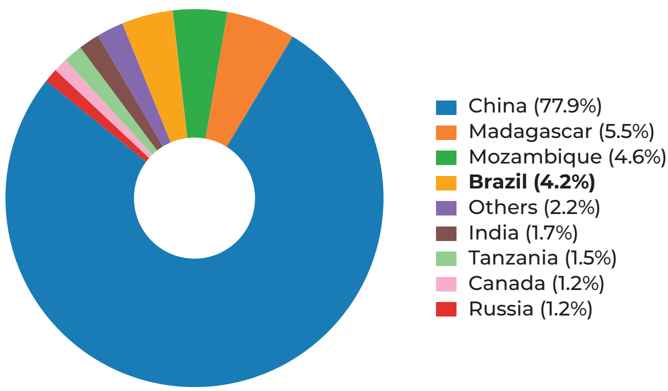
Figure 28. Major applications of graphite



Source: https://natural-resources.canada.ca

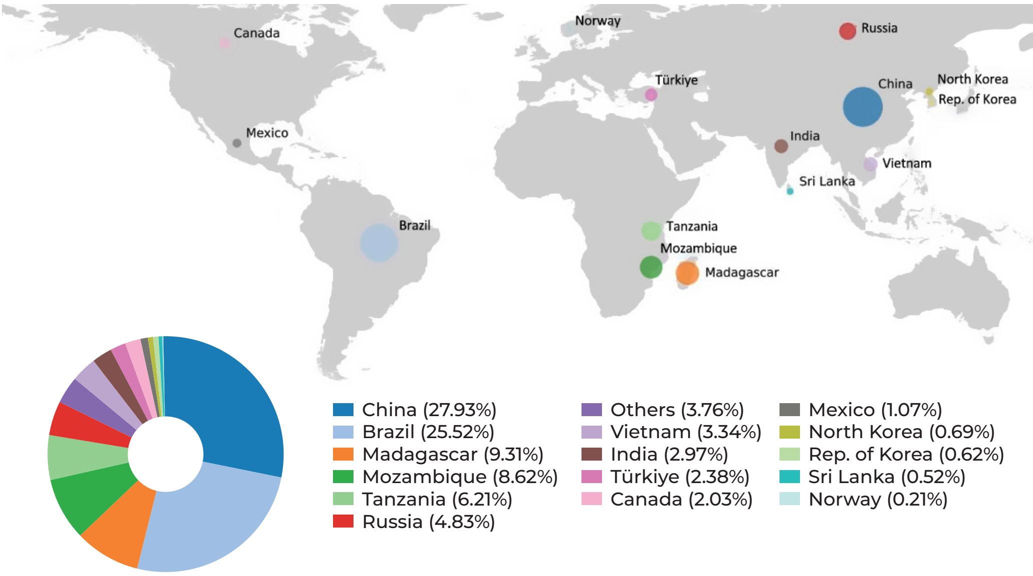
The global landscape is highly concentrated: China produces approximately 78% of natural graphite and 60% of synthetic graphite, and holds nearly one third of reserves. Brazil holds a strategic position with 25.5% of global graphite reserves (≈74 Mt; USGS, 2025) and is the world's fourth-largest producer, contributing roughly 4.2% of global output. Domestic production reached 68,000 tonnes in 2024 (+2.6% year on year); the Santa Cruz Mine (BA) began operations in 2024 and plans to expand from 12,000 to 50,000 tonnes/year.

Figure 29. Share of global graphite production by major producing country



Source: CETEM, 2025

Figure 30. Distribution of global graphite resources

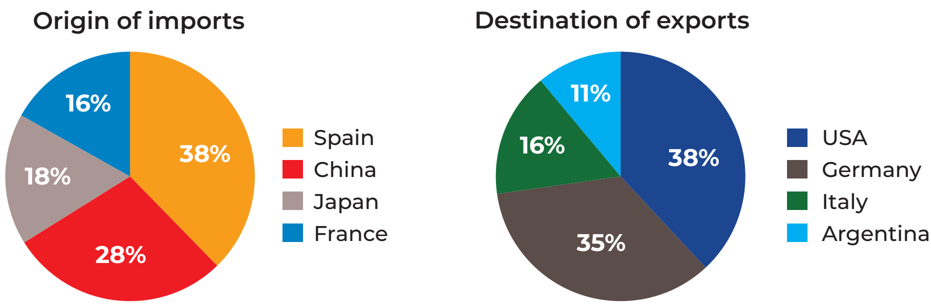


Source: CETEM, 2025

Despite its geological resources and recent growth in production, Brazil remains concentrated in the early stages of the supply chain, with limited domestic processing. The Bahia-Minas Province and the Ceará Graphite Belt are emerging as attractive targets for investment, technological innovation, and the development of anode graphite processing and refining clusters.

Brazil's trade balance showed a USD 42.5 million deficit (2023). Brazil primarily exports raw, natural graphite, and imports refined and synthetic high-value-added products. Major export markets are the USA and Germany; imports come mainly from Spain and China (see figure below).

Figure 31. Origin and destination of Brazil's graphite imports and exports: share by country (%)



Source: Brazilian mineral summary 2024.

The current trade structure confirms Brazil's continued role as a primary product exporter, sustaining a trade deficit and limiting the capture of domestic value. Reversing this situation requires a more robust technological and industrial base - combining innovation, incentives for industrialization and sustainability/traceability standards - to reduce asymmetries, attract CAPEX and secure access to more exigent markets.

Opportunities in graphite

Three integrated approaches can steer projects and partnerships:

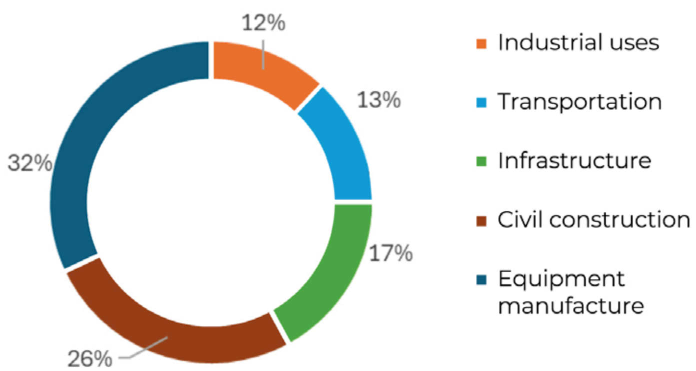
- **Potential for integration of production and enhancement of value:** expanding graphite processing capacity for battery applications (purification and preparation of anode material) to reduce the dependence on imports. Hubs like Bahia, Minas Gerais, and Ceará can attract joint ventures and public-private partnerships to install/expand plants and develop an ecosystem associated with the battery supply chain and electrical components.
- **Technological innovation and sustainability:** engage businesses, institutions such as SGB/CPRM, CETEM and universities to develop pilot projects and demonstration plants, improve product quality and the reuse of industrial waste and batteries (recycling). The SGB (2025) notes that Brazilian geological formations are favorable for high-quality graphite and that significant growth potential exists, supported by government interest in expanding production - providing a springboard for accelerating pilot tests and developing new, environmentally-friendly processing.

- **International cooperation and geopolitical positioning:** establish agreements with battery manufacturers and assemblers for offtake and technology transfer; implement traceability and low-carbon labeling to access more exigent markets; and pursue green financing for midstream projects. With global demand on the rise, this agenda helps position Brazil as a reliable supplier of battery-grade graphite, adhering to competitive ESG standards.

6.2. Copper

Copper is a strategic input for the energy transition and digitalization, owing to its use in solar panels, wind turbines, electric vehicles and charging stations, energy storage systems, smart grids, as well as electronics, telecommunications, and data center applications (Natural Resources Canada, 2025). Its properties - high electrical/thermal conductivity, malleability, and corrosion resistance - support its widespread use in modern infrastructure.

Figure 32. Major global applications of copper

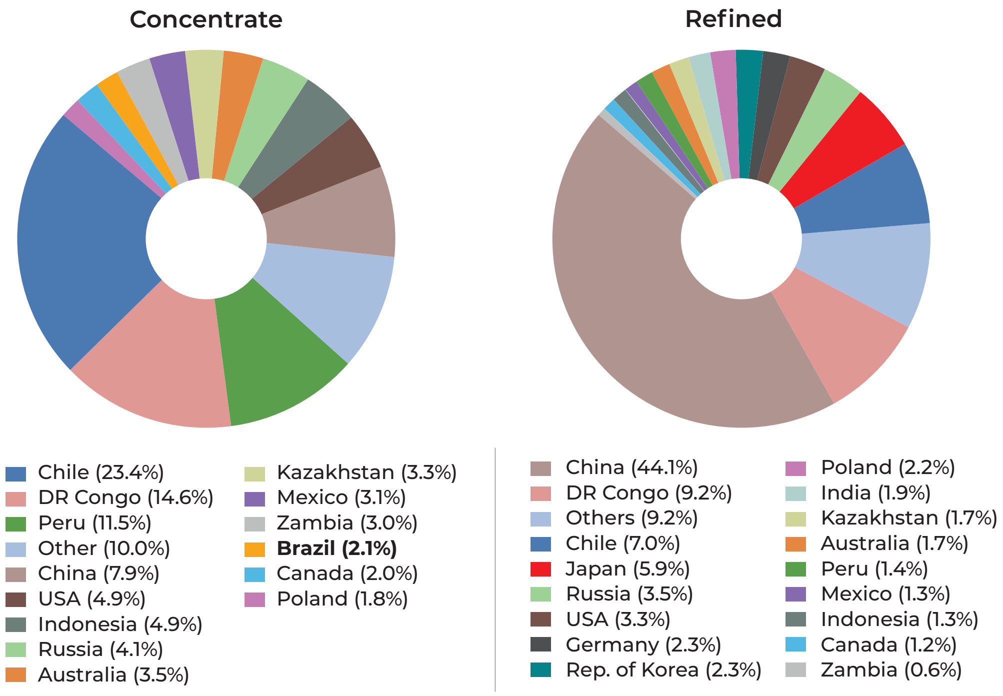


Source: Prepared by the authors based on data from Natural Resources Canada, 2025

Beyond its versatility, copper is a cornerstone of the circular economy, as it fully retains its chemical and physical properties through successive recycling cycles without any loss of performance (ICSG, 2025; Natural Resources Canada, 2024). In 2024, ~150 kt of post-consumer waste were recovered and 720 kt of industrial scrap were reintroduced (USGS, 2025), showing that recycling represents a significant secondary source of copper and has much to contribute in the transition to a low-carbon, material-efficient economy (IBRAM, 2024).

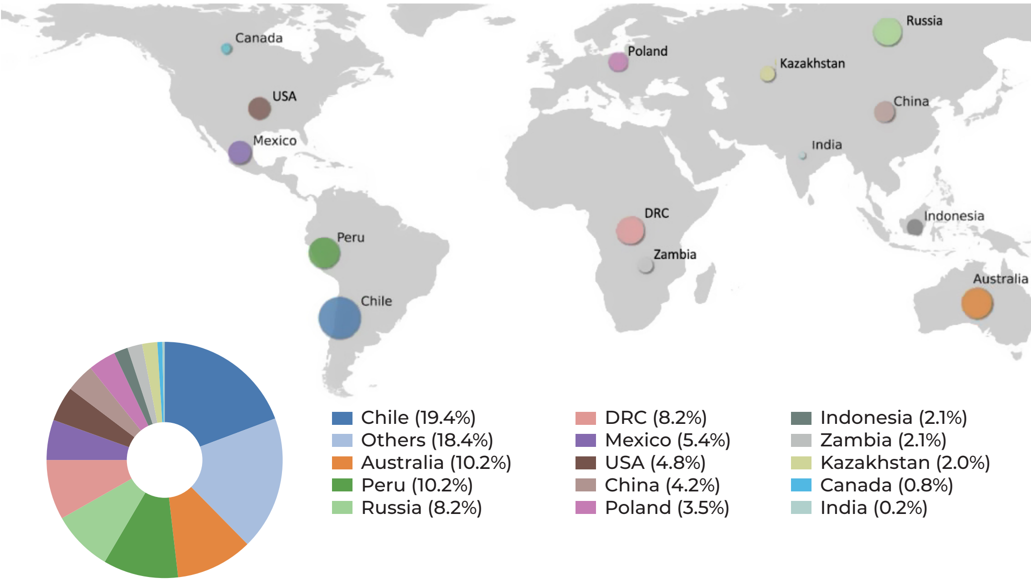
Global production remains concentrated: Chile leads in ore output, followed by the Democratic Republic of Congo, Peru and China - the latter accounting for the largest share of refined copper (Figure below). According to the USGS (2025), global resources total approximately 2.1 billion tonnes (1.5 billion as yet unexplored and 0.6 billion already produced), with an estimated 3.5 billion tonnes yet to be discovered. Brazil ranks 10th globally, with reserves of around 17 million tonnes, representing approximately 1.9% of world total (SGB/MME, 2025) . Brazil's geological endowment is concentrated in the Carajás Mineral Province and in emerging areas of Goiás and Bahia, supporting potential production growth in an increasingly competitive and geopolitically sensitive market.

Figure 33. Share of global copper production by major producing country



Source: CETEM, 2025

Figure 34. Distribution of global copper resources



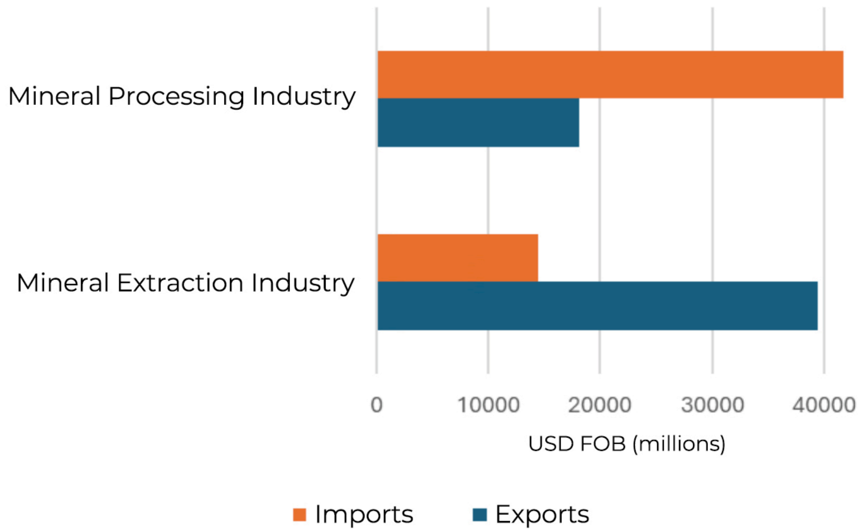
Source: CETEM, 2025

Demand for copper is rising given its wide range of applications across technologies such as electrification and network expansion, but the development of new mines is slow, with growth concentrated in brownfield projects[50]. Metallurgical improvements allow lower-grade ores to be processed, mitigating the depletion of high-grade deposits, yet supply still lags behind demand (Northey, 2014).

Brazil's copper trade balance remains in deficit: the country exports mostly concentrated copper and imports high-value-added refined and manufactured products. The figures below illustrate Brazil's limited domestic industrial integration and its high technological dependence in the refining and processing stages.

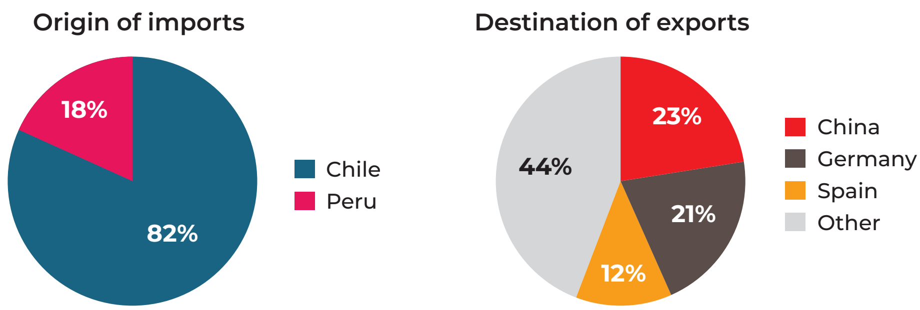
50. In mining, brownfield projects are expansions, reactivations, or new fronts around existing operations, taking advantage of the infrastructure and licenses already in existence.

Figure 35. Import and export of copper products in 2024



Source: CETEM, 2025.

Figure 36. Origin and destination of Brazil's copper imports and exports: share by country (%)



Source: CETEM, 2025.

In short, capturing greater value requires moving further into the midstream segment - from smelting and refining to cathode production, rolling, and wire-sheet manufacturing - supported by competitive energy, efficient logistics, and regulatory predictability. Recycling is a structural lever.

Opportunities in copper

Three integrated approaches can steer projects and partnerships:

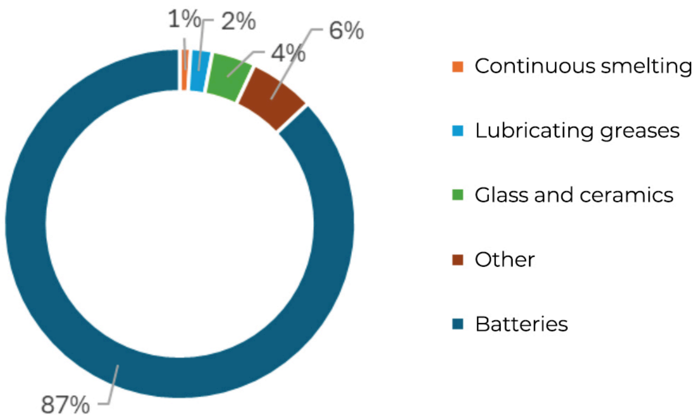
- **Potential for integration of production and enhancement of value:** expanding domestic refining and smelting capacity is essential to reduce the trade deficit and develop copper refining hub in Brazil. Promoting industrial verticalization[51], with incentives for joint ventures and public-private partnerships in hubs such as Carajás, Vale do Curaçá and Goiás, to attract investments in the production of cables, alloys and electrical components.
- **Technological innovation and sustainability:** strengthening the scientific network - spearheaded by federal institutions and universities - can boost Brazil's competitiveness in processing, recycling and refining. Cooperative R&D programs focused on green metallurgy, by-product recovery, and origin traceability are essential for Brazil to successfully integrate into sustainable supply chains. Moreover, recycling should become central pillar of national strategy, to increase the share of secondary copper and reduce pressure on new mining operations.
- **International cooperation and geopolitical positioning:** Brazil has the potential to lead, alongside Chile and Peru, a regional agenda for sustainable copper, predicated upon convergent environmental standards and transparency in supply chains. The formation of a South American copper cluster, structured around innovation, energy efficiency, and ESG certification, will strengthen Brazil's position in forums such as the G20 and COP 30, enhancing Brazilian influence in the global governance of critical minerals.

6.3. Lithium

Lithium is an alkali metal whose unique physical and chemical properties - low density, high electrochemical potential, and high reactivity with electrolytes - place it at the center of the race for cleaner and more efficient energy sources. Long used in lubricating greases, pharmaceuticals, ceramics, and glass, lithium has in recent years emerged as a critical input for batteries powering electric and hybrid vehicles. It is estimated that 87% of current global consumption is allocated to batteries, while the remaining 13% is distributed across industrial and consumer applications (USGS, 2025).

51. Achieving vertical integration in the mineral supply chain requires reindustrialization and demand levels that make higher-value-added activities, such as beneficiation, refining, and industrial processing, economically feasible.

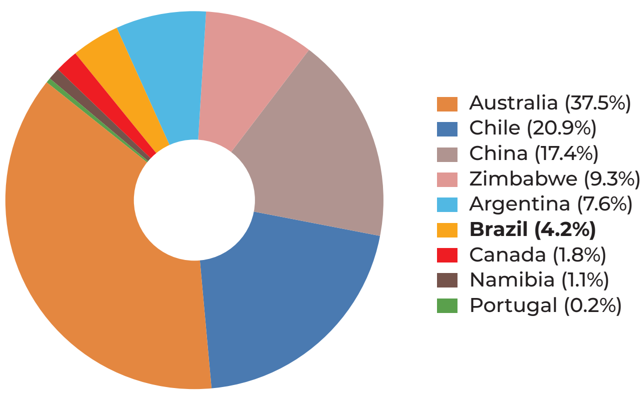
Figure 37. Major applications of lithium



Source: CETEM, 2025.

In 2024, the global lithium supply reached ≈240,000 t LCE (+18% vs. 2023). Production remains geographically concentrated in Australia (≈91.7 kt), Chile (≈41.4 kt), China (≈35.7 kt) and Argentina (≈8.63 kt) (USGS, 2025). Despite advances in capacity, the supply chain remains geographically concentrated and vulnerable to supply shocks. Global resources total ~115 Mt, with approximately ~59.3 Mt located in Latin America. Reserves total ~30 Mt, with Chile accounting for 31% and Australia for 23.3% (USGS, 2025).

Figure 38. Share of global lithium production by major producing country[52]

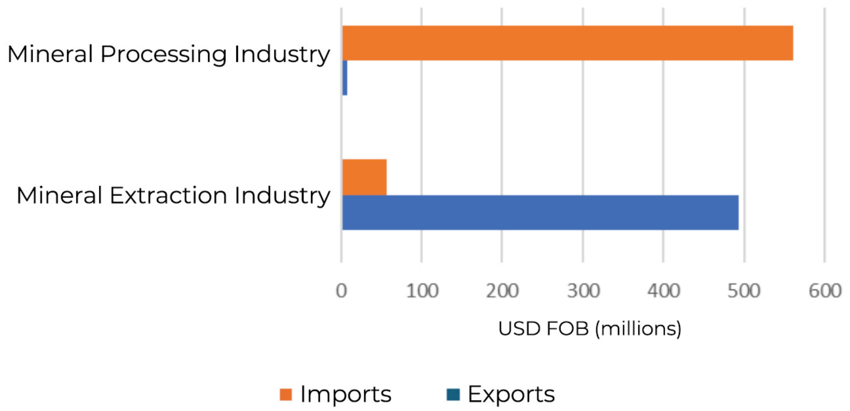


Source: CETEM, 2025.

52. Production from the US and other countries has not been reported (Source: USGS, 2025).

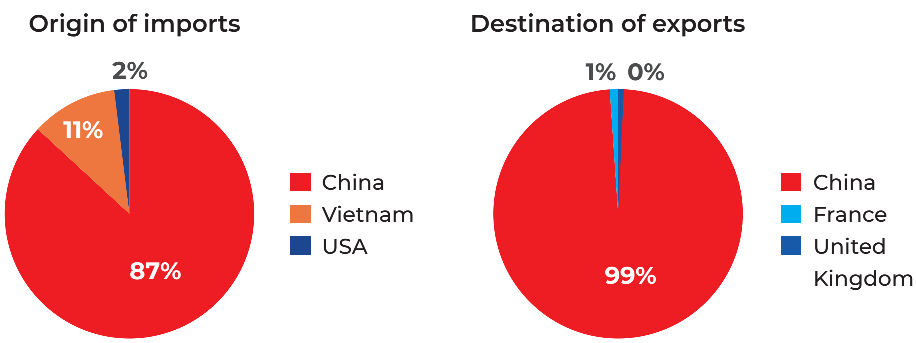
In 2023, Brazil produced roughly 263,900 tonnes of spodumene concentrate - the primary mineral used in lithium production - with 5.7% average Li_2O grade, equivalent to approximately 15,200 tonnes of lithium oxide. Despite this growth, the lithium trade balance remained negative at USD 60.3 million, reflecting the dependence on imported processed products. The figures below show a breakdown of Brazilian foreign trade and the geographical distribution of its main trading partners.

Figure 39. Import and export of lithium products in 2023



Source: Brazilian mineral summary, 2024.

Figure 40. Origin and destination of Brazil's lithium imports and exports: share by country (%)



Source: Brazilian mineral summary, 2024.

In summary, the combination of strong demand, a substantial geological base, and a persistent trade deficit underscore the need of adding more value domestically in lithium-related routes - from concentrate refining to the production of battery-grade compounds and the enhanced recycling.

Opportunities in lithium

Three integrated approaches can steer projects and partnerships:

- **Potential for integration of production and enhancement of value:** the opportunity lies in positioning Brazil as a competitive producer of "green" lithium by domestically processing LCT (spodumene) deposits into battery-grade lithium (carbonate/hydroxide). The operating and ramp-up projects in Minas Gerais' Lithium Valley - including CBL, Sigma Lithium, Atlas Lithium, Lithium Ionic, and the Colina project (Pilbara Minerals) - already form a cluster well-suited for conversion plants and securing long-term contracts with cathode and cell manufacturers, boosting local content and predictability (SGB-CPRM, 2025). Achieving vertical integration requires demand levels that make higher-value-added activities, such as beneficiation, refining, and industrial processing, economically feasible.

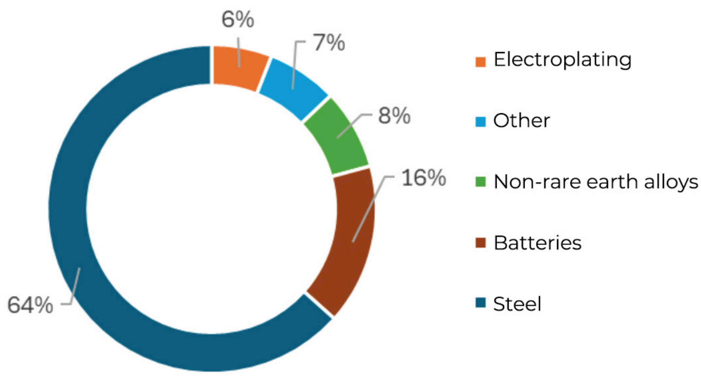
- **Technological innovation, circularity and skill development:** hydrometallurgical routes for lithium conversion and recovery from end-of-life batteries and pyrometallurgical slag are gaining traction, as well as metrology to meet battery-grade specifications. Through their work in eastern Minas Gerais and Solonópole (Ceará), SGB and CPRM have pinpointed targets and mitigated geological risks in the Jequitinhonha and Borborema provinces, paving the way for pilot projects and environmentally sensitive mining routes (SGB-CPRM, 2025; Kresse et al., 2025; Brückner et al., 2020).

- **Cooperation across jurisdictions and frontier expansion:** although Minas Gerais remains in the lead, significant potential exists in the Northeast (Ceará, Rio Grande do Norte, Paraíba) and in greenfield areas of southern Tocantins-northern Goiás and in Itambé (BA). Regional arrangements that integrate mining, conversion, and logistics, coupled with traceability and transparency standards, and partnerships with global players can speed up midstream development and enhance predictability for growth (SGB-CPRM, 2025).

6.4. Nickel

Nickel's corrosion resistance, toughness and ductility make it an essential transition metal for modern industrial applications, such as high-performance metal alloys, and the energy transition. Currently, around 64% of global nickel demand is for stainless steel production (see figure 41), with additional uses chemicals, shipbuilding, food processing, electroplating, alloys for aircraft turbines, thermal power plants, and oil and gas equipment. Nickel is also critical for emerging technologies, forming a major part of high-energy-density cathodes in NMC (nickel-manganese-cobalt) and NCA (nickel-cobalt-aluminum) batteries, which provide greater range for electric vehicles and improve stationary storage performance systems.

Figure 41. Major applications of nickel

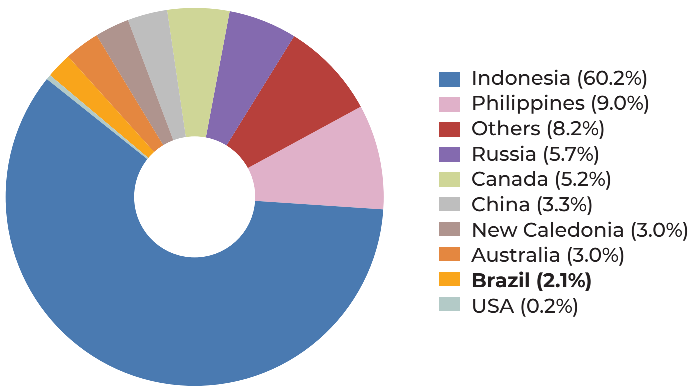


Source: CETEM, 2025.

Global nickel resources exceed 350 million tonnes, with roughly 54% in lateritic deposits, 35% in sulfide deposits, 10% in marine nodules, and 1% in other sources (USGS, 2025). This distribution directly affects processing methods, production costs, and the geographic concentration of supply. Global production is highly concentrated in Indonesia, which accounts for over 60% of the total, while Brazil contributes approximately 3% (Figure 42).

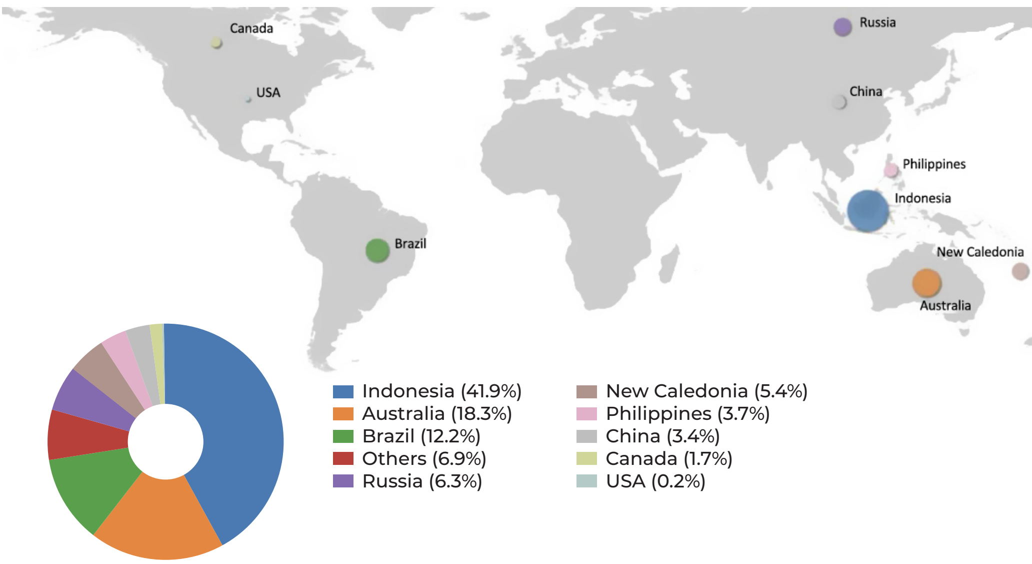
The concentration of production contrasts with a more dispersed distribution of resources: Indonesia continues to lead with 41.7% of known resources, while countries such as Australia (18.3%), Brazil (6.3%) and Russia (5.4%) also possess substantial reserves (Figure 33). This geographic distribution underscores not only Indonesia's current dominance in production, but also the potential for emerging producers, including Brazil, to expand their share in the global supply chain as new projects come online and processing technologies evolver.

Figure 42. Share of global nickel production by major producing country



Source: CETEM, 2025.

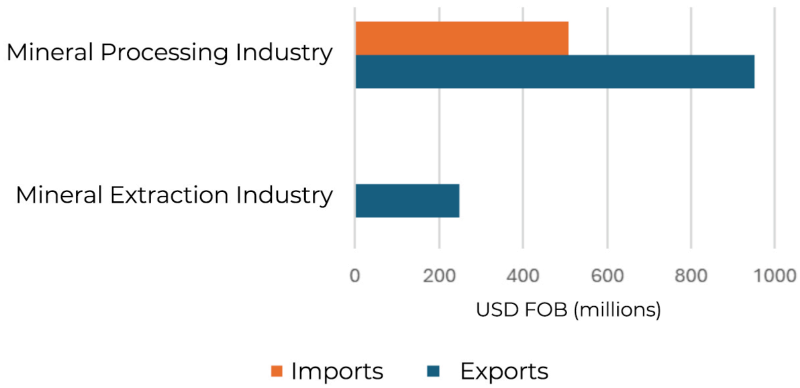
Figure 43. Distribution of global nickel resources



Source: CETEM, 2025.

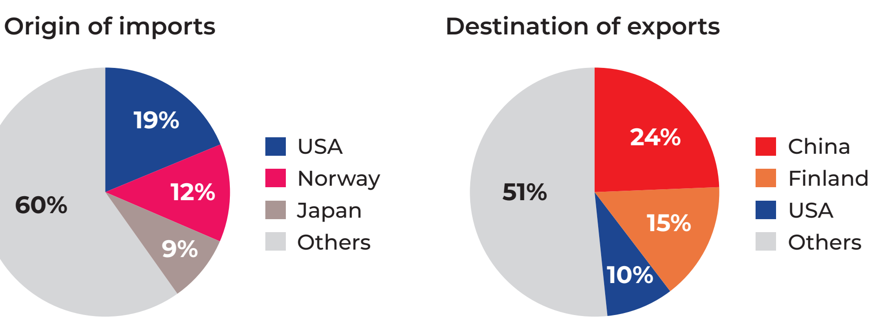
In 2023, Brazil's nickel output - measured in contained metal - reached 72,398 tonnes, and the trade balance for nickel products showed a USD 668.9 million surplus. Exports were concentrated in processed products, while imports were limited to manufactured items reflecting an industrial base capable of adding value to parts of the chain, yet still dependent on specific components from the manufacturing sector.

Figure 44. Import and export of nickel products in 2023



Source: Brazilian mineral summary, 2024.

Figure 45. Origin and destination of Brazil's nickel imports and exports: share by country (%)



Source: Brazilian mineral summary, 2024.

Recyclability is one of nickel's main advantages: it can be recovered repeatedly without any loss of quality. Approximately 68% of the nickel used in stainless steels and other metal products comes from recycled sources. Recycled lithium-ion batteries are increasingly becoming a significant source of secondary nickel, supporting the circular economy and alleviating pressure on primary mining operations.

Brazil's position reflects its production capacity, positive trade balance, and diverse range of applications, from stainless steel to energy transition technologies. Progressing through the midstream stages of the supply chain - particularly in the battery segment - and establishing production arrangements supported by competitive energy, efficient logistics, and regulatory predictability can enhance the domestic capture of value and reinforce recycling as a cornerstone of supply.

Opportunities in nickel

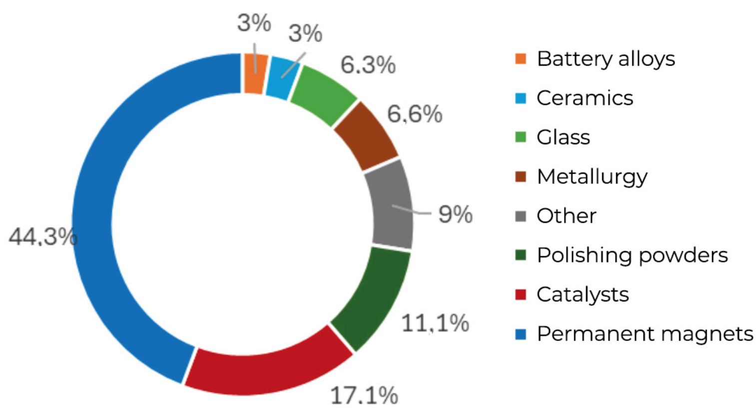
Three integrated approaches can steer projects and partnerships:

- **Potential for integration of production and enhancement of value:** leverage different types of nickel deposits - lateritic and sulfide - and develop domestic processing, moving from the production of basic alloys like ferronickel to higher-grade and higher-value products, such as class I nickel and nickel sulfate for batteries. The current operational base - including the Onça-Puma, CODEMIN, Barro Alto and Santa Rita mines, three of which operate below the global cost average - provides scale and favorable conditions to bolster domestic production and provide a more stable supply for both the domestic market and global cathode and battery chains (SGB-CPRM, 2025).
- **Technological innovation, circularity and skill development:** expanding hydrometallurgical routes for laterites (including HPAL where applicable) and optimizing sulfide processing routes (such as Jaguar, with enrichment in millerite and high-quality concentrates), while integrating cobalt recovery as a co-product and recycling lithium-ion batteries to strengthen the secondary supply. Pilot studies and demonstration projects, incorporating metrology and quality control aligned with battery specifications, will help reduce technological risk and accelerate industrial development. (SGB-CPRM, 2025; USGS, 2023).
- **Cooperation across jurisdictions and competitive energy:** leverage access to low-cost, low-emission hydroelectric power to reduce both carbon footprint and unit costs, while fostering industrial clusters near operations and projects - such as Araguaia (PA/TO), Piauí (PI), Jaguar (PA), and the new Lagoa Grande deposit (BA-PI, ~405 Mt estimated) - with integrated logistics and regulatory predictability. This configuration supports the production of low-carbon class I nickel and strengthens Brazil's position in the global battery and stainless steel supply chains (SGB-CPRM, 2025).

6.5. Rare earths (REE)

Among the 17 rare earth elements (REE), four stand out for their strategic role in the energy transition: neodymium (Nd), praseodymium (Pr), dysprosium (Dy) and terbium (Tb). Essential for producing high-performance permanent magnets, rare earth elements are critical to the operation of electric vehicle engines, wind turbine generators, and other low-carbon technologies (Natural Resources Canada, 2025). In 2023, the use of REEs in magnets accounted for 44.3% of global demand, and the four selected magnetic elements rank among the most valuable within the group - see table 30.

Figure 46. Major applications of REE



Source: CETEM, 2025.

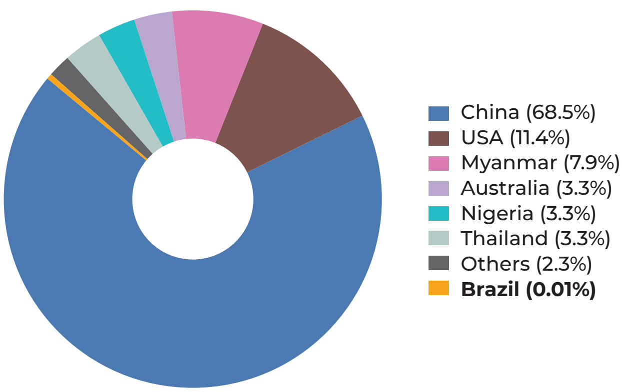
Table 30. Average price (USD /Kg) of different REE

REE	Average price Feb 2024-Jan 2025 (USD/kg)
Ce	1.11
Dy	320.97
Er	42.62
Eu	24.58
La	1.84
Nd	68.12
Pr	71.02
Sm	10.86
Tb	988.99
Y	29.45

Source: CETEM, 2025.

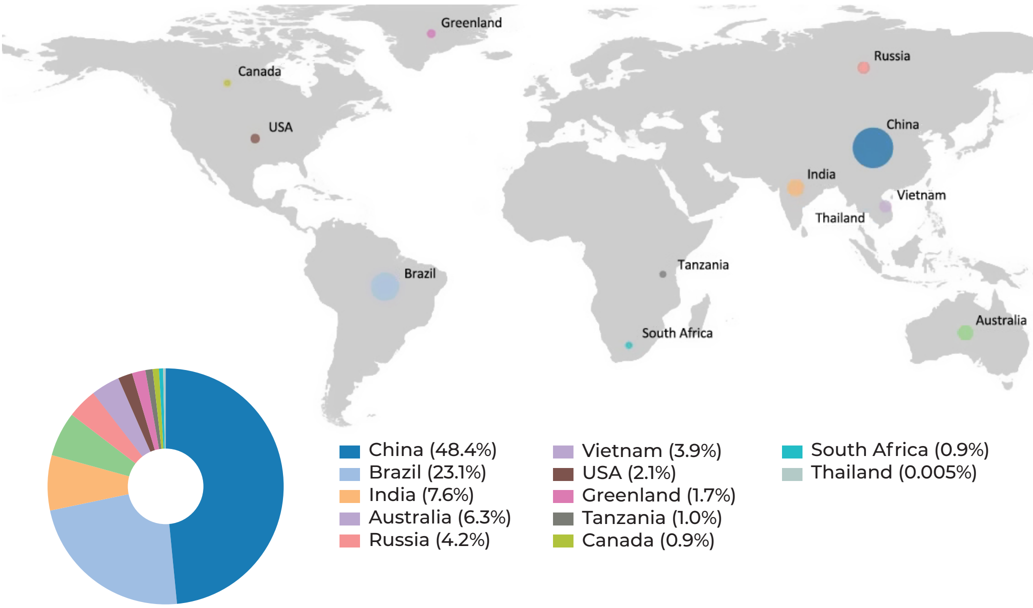
The global rare earths market is highly concentrated: China accounts for approximately 70% of production and nearly the entire processing chain, reinforcing geopolitical concerns and putting pressure on consumer countries to diversify their suppliers. Brazil holds a strategic position as holder of the world's second largest reserves, behind only China (CETEM, 2025). Figures 47 and 48 show the concentration of global production and the distribution of resources, underscoring the need to develop new production centers.

Figure 47. Share of global REE production by major producing country



Source: CETEM, 2025.

Figure 48. Distribution of global REE resources



Source: CETEM, 2025.

Domestic production is still incipient. Mineração Serra Verde, Brazil's sole REE operation, commenced activities in 2024 and is ramping up production to reach 5,000 tonnes of oxides per year. More detailed production and trade balance information including this operation are not as yet available. Nevertheless, the presence of substantial reserves and the commencement of primary production position Brazil to increase its participation in global value chains, especially if Brazil succeeds in developing domestic processing and refining capacities - stages that remain concentrated abroad.

REE recyclability opens up an additional strategic opportunity. REEs can be recovered from electronic waste, such as printed circuit boards, NdFeB permanent magnets, spent fluorescent lamps, and NiMH batteries, through pyrometallurgical, hydrometallurgical processes and more recent solvent extraction techniques. By expanding its recycling capability, Brazil can reduce dependence on primary mining and mitigate exposure to geopolitical risks and price volatility.

Opportunities in rare earths

Three integrated approaches can steer projects and partnerships:

- **Potential for integration of production and enhancement of value:** the presence of significant reserves - approximately 21 Mt, the second largest globally (USGS, 2025) - offers Brazil a strategic base to move up the REE value chain, reducing its dependence on primary extraction. The Mineração Serra Verde operation in Minaçu (GO), targeting an annual output of 5,000 tonnes of rare earth oxides in its Phase I, represents an initial milestone, but expansion of separation and individual-element refining is needed to allow Brazil to produce higher-value compounds for high-performance permanent magnets. REE recovery as co-products in existing niobium and phosphate operations, such as those in Araxá, Catalão, Poços de Caldas, Tapira and Pitinga, currently under feasibility studies, offers an opportunity to enhance vertical integration.

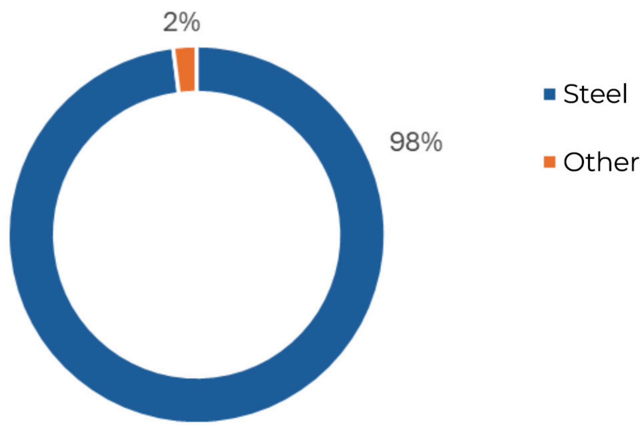
- **Technological innovation, circularity and new materials:** strengthening recycling routes for industrial and electronic waste - such as NdFeB magnets, circuit boards, and fluorescent lamps - will open up the opportunity to expand secondary supply and reduce geopolitical vulnerability. Pyrometallurgical, hydrometallurgical, and solvent extraction processes are under development for this purpose and can be advanced through partnerships between research centers and businesses. At the same time, R&D programs should investigate technological alternatives that ease pressure on primary supply, including ferronitride alloys and tetraenite, which can partially substitute for magnetic REEs in specific applications. Redesigning devices and systems to reduce the use of these elements without sacrificing technical performance is also emerging as a significant focus of innovation.

- **Cooperation across jurisdictions and strategic positioning:** the distribution of Brazilian deposits - which include Araxá, Catalão, Tapira, Poços de Caldas, Seis Lagos and Repartimento - creates opportunities to develop territorial clusters integrated with competitive logistics and energy infrastructure. Coordination with public policies and financial support for strategic projects can accelerate the vertical integration of the supply chain and bolster Brazil's position as a reliable supplier. In parallel, cooperation with other South American producing countries and global technology centers will enable Brazil to align with international standards of traceability, sustainability, and environmental certification, which are becoming increasingly necessary to access strategic markets.

6.6. Iron

Iron ore is one of the most abundant and economically significant raw materials on the planet, serving as the primary source for the extraction of iron (Fe), an indispensable element for modern industry. Its properties - high mechanical strength, ductility, malleability, and thermal conductivity - make it essential for forming metal alloys, particularly with carbon to produce steel. Steel accounts for approximately 98% of global iron consumption (see Figure 49) and plays a key role in industries such as civil construction, transportation, capital goods, metal packaging, and durable goods. Iron is also directly used in the manufacture of industrial components such as engines, valves and gears. Its strategic importance extends to production and logistics infrastructure, giving a competitive edge to countries with large reserves and production capacity, such as Brazil.

Figure 49. Major applications of iron ore



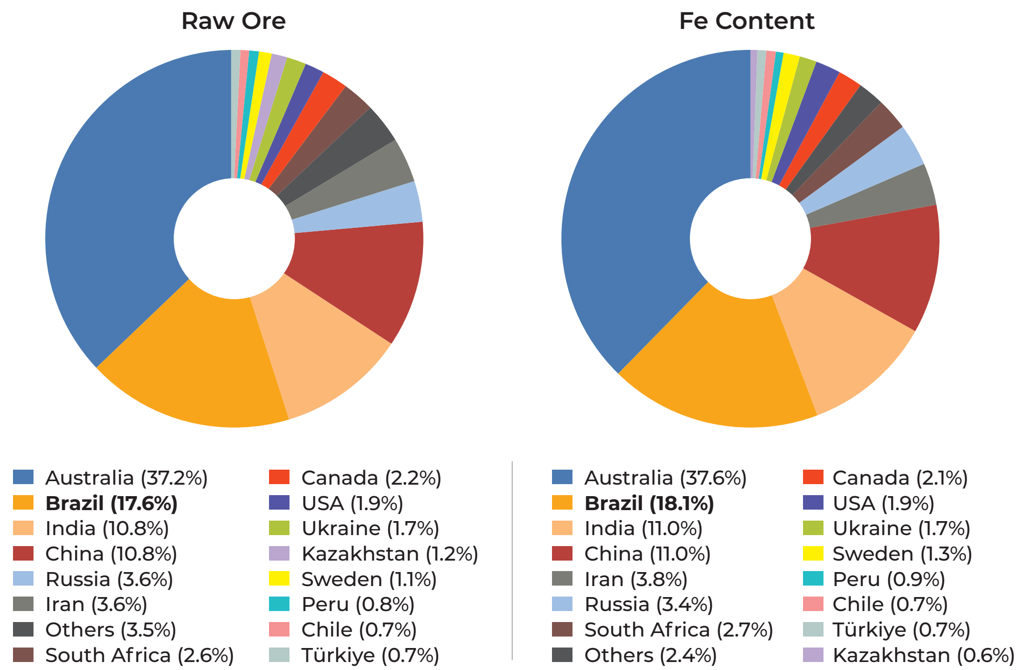
Source: CETEM, 2025.

In addition to its economic importance, iron ore plays a strategic role in the energy transition. Countries such as Australia, South Africa and China have designated high-purity ores as critical minerals, reflecting their importance for low-carbon technologies. Iron and steel are essential in the manufacture and construction of wind turbines, solar panels, electrified rail systems, hydropower plants, and electric vehicle charging stations.

At the same time, the steel industry accounts for about 8% of global CO2 emissions, making its decarbonization critical for achieving climate targets. The use of high-quality ore is crucial for cleaner production methods, such as direct reduction (DRI) and electric arc furnaces (EAF), which significantly reduce emissions compared to traditional processes.

The global iron ore market is concentrated: Australia accounts for approximately 37% of world production, followed by Brazil with 17.6%, China with 10.8%, and India with 10.8% - see Figure 50 (USGS, 2025). China dominates consumption, taking more than 70% of global imports, followed by Japan (6%) and South Korea (4.5%) (TradeMap). Despite a slowdown in the construction, automotive, and manufacturing sectors over the past year, global demand was sustained by investments in public infrastructure and climate mitigation projects - a trend expected to continue even as China's civil construction and manufacturing slow down.

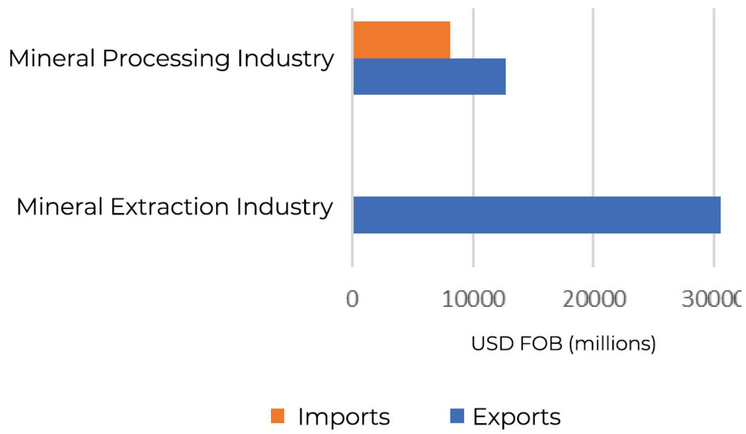
Figure 50. Share of global iron ore production by major producing country



Source: CETEM, 2025.

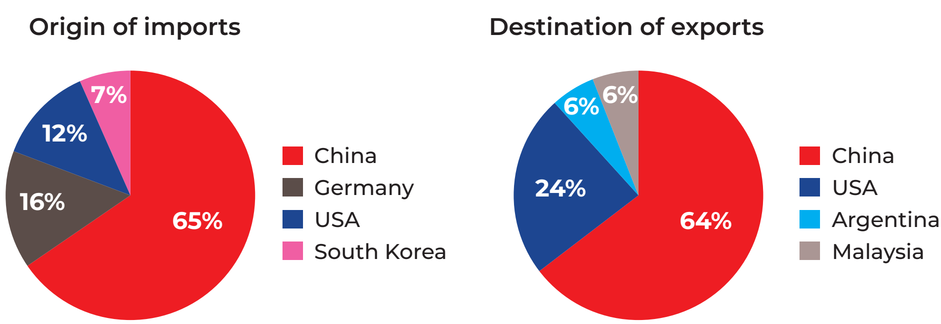
Brazil's production of processed iron ore reached 436.8 million tonnes in 2023, with 62.7% average iron grade. The trade balance showed a significant surplus (USD 35.1 billion) in that same year. The figures below show a breakdown of Brazilian foreign trade and the geographical distribution of its main trading partners.

Figure 51. Import and export of iron ore in 2023



Source: Brazilian mineral summary, 2024.

Figure 52. Origin and destination of Brazil's iron ore imports and exports: share by country (%)



Source: Brazilian mineral summary, 2024..

Steel's recyclability is another strategic component of the supply chain, as steel can be reprocessed indefinitely without loss of quality, greatly reducing the consumption of energy and raw materials. The production of steel in electric arc furnaces - which use only metal scrap - greatly reduces energy consumption compared to traditional ore-based methods. Since 1960, the energy required to produce one tonne of steel has decreased by approximately 40%, illustrating how recycling and technological advances can substantially reduce the industry's carbon footprint.

Opportunities in iron ore

Three integrated approaches can steer projects and partnerships:

- **Potential for integration of production and enhancement of value:** Brazil's substantial geological endowment - around 34 billion tonnes of raw ore, the third largest globally, and 15 billion tonnes of contained iron, the second largest - provide a strong basis from which to move up the value chain and reduce dependence on raw ore exports. The existing production structure, dominated by Vale S.A., features large-scale operations in Carajás (Serra Norte and S11D) and the Iron Quadrangle, integrated with dedicated logistics systems for transportation and distribution. Expanding beyond this production base into processing stages - from pig iron to higher value-added steel - requires demand levels that make these operations economically feasible.
- **Technological innovation, circularity and decarbonization of the steel industry:** reducing the carbon footprint of the steel industry, which accounts for roughly 8% of global CO2 emissions, is key to align iron and steel production with climate targets. High-quality ore enables cleaner production routes, such as direct reduction (DRI) and electric arc furnaces (EAF), which emit far less than traditional blast furnaces. Strengthening R&D networks in green metallurgy, optimizing itabirite beneficiation, and recovering byproducts can accelerate the technological transition. Steel recycling, which enables complete reuse without loss of quality, is also emerging as a strategic focus: since 1960, the energy required to produce one tonne has decreased by approximately 40%, illustrating how circular routes can curb emissions and increase efficiency.
- **Cooperation across jurisdictions and competitive infrastructure:** the large scale of production and the low price per tonne require robust logistics infrastructure, particularly railroads and ports, to ensure efficient flow and reduce operating costs. The development of industrial

clusters near major mining areas - in Minas Gerais, Pará, Bahia and Mato Grosso do Sul - can create production synergies, foster industrialization, and accelerate the transition to low-carbon technologies. Moreover, coordination with public policies and international partnerships will enhance Brazil's position in global steel and green infrastructure supply chains, securing access to markets with more stringent sustainability, traceability, and environmental standards.

7.

Public Policy Recommendations

Strengthening Brazil's position in critical and strategic mineral (CSM) supply chains requires coordinated regulatory, technological, financial and diplomatic actions. The diagnosis in this report points to structural obstacles - sluggish and fragmented licensing, overlapping authorities, gaps in geological mapping, limited incentives for value addition, and poor integration among research, industry, and innovation - while also identifying numerous opportunities for increased production and global energy transition supply chains. Drawing on these results and on a literature review, the recommendations below focus on high-impact short- and medium-term actions to foster research, responsible mining, processing, and innovation, adhering to the sustainability and traceability requirements expected by demanding markets.

I. **Enhance the mining sector's regulatory framework** by improving coordination among agencies and streamlining decision-making processes. Expedite the creation of legal and regulatory frameworks that include broad social participation and provide legal certainty, so as to build a modern, transparent, and efficient environment. Establishing specific, integrated legislation for the sector, alongside strengthening the National Council for Mineral Policy (CNPM) as a priority-setting body, will be a decisive step. This modernization should align with existing national policies, such as the Ecological Transformation Plan (PTE), New Industry Brazil policy (NIB), PLANTE and PlanGeo, to provide institutional coherence and continuity between the mineral, energy, and industrial agendas. Finally, coordinating initiatives across federal, state and municipal levels on the climate agenda is essential to align sectoral policies and harmonize regulatory frameworks.

II. **Strengthen mechanisms to attract funding and investments,** including development of novel financial instruments such as green, social, sustainable and other types of sustainability-related bonds (see FINEP-BNDES, initiatives within the Ecological Transformation Plan and BNDES investment funds[53]). Given its strategic importance, it is necessary to reinforce an integrated approach that recognizes mining's key role in clean technology supply chains and the low-carbon economy, thereby facilitating access to climate finance mechanisms and favorable credit lines for sustainable mining projects.

III. **Invest in new business models that encourage the participation of regional players.** Foster innovation, R&D and models that integrate science, technology and industry (pilot plants, demonstrations and business-academia-government consortia), to reduce dependence on imports in purification/refining stages and increase the vertical supply chain integration - for example, in graphite for anodes, refined copper, and recycling. Furthermore, prioritize hubs that combine existing mineral resources and industrial potential with technical and institutional training programs focused on sustainability.

IV. **Develop the industrial infrastructure and boost regional connectivity** through robust investments in strategic interconnectors such as power grids, pipelines, railways, highways and ports, in addition to encouraging the creation of border markets. Modernizing the mining sector also requires technologies that help curb emissions, optimize resource use, recycle waste, and electrify fleets. These advancements require long-term funding, which is often inaccessible through traditional channels. All of the above make it essential to strengthen innovation and capacity-building mechanisms, especially for small and medium-sized enterprises.

V. **Build a regional agenda for energy and minerals** that incorporates coordination mechanisms for crisis response and expanded regional

53. See the "Financiamento Climático e Mineração" report (IBRAM, 2025b).

collaboration. These efforts can enhance economic and political stability and facilitate integrated infrastructure and regulation planning. Moreover, forging alliances with nations and economic blocs, prioritizing technological cooperation agreements, can boost Brazil's and Latin America's integration into global value chains.

VI. **Upgrade and modernize Brazil's geological mapping,** prioritizing the reduction of regional asymmetries - especially in the Amazon region - and expand detailed-scale coverage (1:100,000 and 1:50,000), is essential to improve basic geoscientific knowledge and guide investments, funding, and public policies in the mineral sector. Supporting PlanGeo 2025-2034 as a state policy can secure budgetary continuity, institutional integration, and the use of geospatial and remote sensing technologies, thereby increasing data accuracy and Brazil's appeal for new sustainable mining, environmental, and land-use projects.

VII. **Create identification instruments for strategic supply chains in Brazil** by designed strategic roadmaps and technological prioritization agendas for critical and strategic minerals (CSM), in line with Mission 3 of the New Industry Brazil policy, which proposes to "encourage value-adding mineral activities in Brazil". These instruments should facilitate pinpointing supply chains with the highest competitive and technological potential, promote coordination among R&D, innovation, industrial, and financing policies, and foster cooperation across ministries, state governments, and the private sector.

VIII. **Encourage sustainable mining practices that adhere to high environmental, social and governance (ESG) standards**, minimizing negative impacts while maximizing potential and the economic and social well-being of the population, given that mining's social and-environmental impacts affect local communities throughout its entire cycle, from prospecting to post-closure, but its economic benefits are not always equitably distributed among stakeholders. Resolving this tension is fundamental to support a just energy transition and enhance the sustainability of mining operations.

IX. **Stimulate the circular economy in mining:** Promote nationwide recycling programs for critical minerals, supporting pilot projects in urban mining and the reclamation of degraded areas. These initiatives alleviate pressure on new exploration frontiers, stimulate local value chains, and reinforce social and environmental sustainability.

X. **Promote strategic alignment between Brazil's geological potential and emerging industrial needs.** Align mineral supply with industrial demand by building planning mechanisms that connect Brazil's geological potential to the needs of emerging industrial chains (batteries, hydrogen, electrification). Anticipate supply bottlenecks and coordinate short- and medium-term sectoral plans is essential to align mineral exploration, industrial policy, and the energy transition - converting natural resources into production and technological capabilities.

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Appendix A
Methodology

To estimate the potential supply of CSM, this study primarily used the database of the Geological Survey of Brazil (SGB), which consolidates information on mineral deposits and occurrences for a wide range of commodities nationwide. The data were collected from multiple sources, including field surveys, internal reports, research on mining company websites, and official reports and publications from regulatory and development agencies, such as the National Mining Agency (ANM), the Brazilian Mining Association (IBRAM) and the Ministry of Mines and Energy (MME). This study also drew on data from academic literature, including theses, dissertations and scientific papers, as well as historical information and records obtained through direct communication with experts in the field.

The estimation of mineral supply potential sought to calculate the maximum amount of a mineral can be recovered from a given ore, based on its chemical composition, the grade of the element of interest, and conversion factors derived from stoichiometric relationships and the molar masses of the relevant compounds. Element grades (expressed as a percentage of the oxide or element present in the ore) were converted into contained mineral mass using specific equations that relate the percentage content to total available mass.

The upper limit of potential supply was estimated using a theoretical approach to total recovery that excluded operational losses during mining, beneficiation or processing. This assumption reflects the theoretical maximum potential of the resource, disregarding technological, economic and logistics limitations.

It is important to emphasize that estimates of mineral resources and reserves are not exact values, but rather projections derived from the data available and standardized physical and chemical parameters. In practice, losses occur at different production stages, depending on ore quality, equipment efficiency, and operating practices. Accordingly, the results presented in this report should be interpreted as a theoretical reference, useful for comparison and strategic planning, not as definitive recoverable volumes.

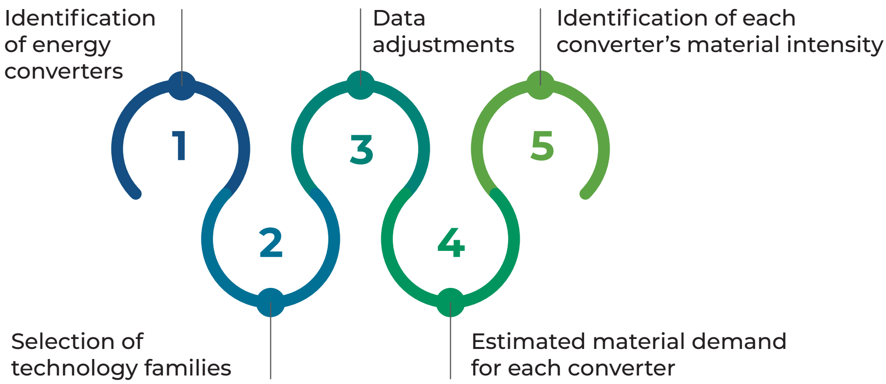
The demand for materials projected in the first stage of this study centered on identifying major energy converter groups for 2025-2050 based on BLUES modeling results for the Brazil Transition scenario. The most promising technology converter families were then selected through a review of technical and scientific literature, guided by technical, economic and environmental criteria. The selection of these families is paramount for advancing the investigation, which aims to determine material demand associated with key energy transition converters.

The demand for materials was subsequently estimated based on key energy transition equipment, organized into subcategories: stationary storage batteries; vehicle batteries - including buses, battery-powered trucks, light vehicles and light commercial vehicles; fuel cells; electric motors; wind turbine generators; and photovoltaic panels.

After defining the components included in the analysis and their rationale, the materials directly incorporated into each technology were quantified to determine the inputs present in each converter after its manufacture, excluding production losses. The material demand calculated can be assumed to indicate the net demand used for each converter examined within the scope of the aspects considered in the analysis.

Figure 53 illustrates the methodological flow used in this study, from the BLUES model to the calculation of material demand for the converters selected.

Figure 53. Methodological steps



Source: Prepared by the authors.

The Brazil Transition Scenario (BT) used by the BLUES model to estimate material demand for energy converters is derived from the Energy Transition Program (ETP). Phase 2 of the Program encompasses three scenarios that operate as quantitative narratives to inform the strategic planning of Brazil's energy transition. Each scenario reflects varying levels of climate ambition, economic, technological, and political constraints, providing an analytical basis to debate potential pathways toward climate neutrality and emission scenarios. As it represents the lowest-cost route to fully achieve Brazil's Nationally Determined Contribution (NDC), the Brazil Transition Scenario (BT) is at the core of this study, and was used as an input to support its development. The BT scenario assumes that Brazil will pursue full compliance with its NDC targets.

This scenario envisions a reduction of approximately 50% in net GHG emissions by 2030 compared to 2005 levels, and achieving zero net emissions by 2050. This scenario further assumes adherence to land use commitments, in particular zero illegal deforestation, and the restoration of 12 million hectares of forest by 2030, in line with the National Plan for the Recovery of Native Vegetation (PLANAVEG).

ETP scenarios were constructed using a quantitative approach supported by the BLUES (Brazilian Land-Use and Energy Systems) integrated analysis model developed by the Cenergia (Coppe/UFRJ). This model enables the integrated analysis of energy systems, land use, and greenhouse gas (GHG) emissions, serving as a tool to evaluate decarbonization routes that balance technical feasibility, cost-efficiency, and climate targets. Its integration with the COFFEE global model allows BLUES to evaluate the consistency of national scenarios with international emissions thresholds. BLUES play a key role in the ETP, both by generating sectoral pathways and assessing their implications for investments, infrastructure, and public policy.

Appendix B
Intensity and materials selected for analysis

The estimate covers both new capacity additions and capacity replacements - i.e., the materials needed to replace equipment that reaches the end of its operating life, based on specific average durability rates for each technology. Based on the energy converters selected, the total demand for a material "i" over time was calculated as the sum of additional demands for each technological route "j" and technology "k", as shown in Equation 1:

$$DM_i = \sum_t \sum_j \sum_k (CI_{jt} \cdot PT_{jk} \cdot IM_{ik})$$

This demand is estimated based on the additional installed capacity for each technological route "j" (CIjt), weighted by the temporal penetration of each technology family or specific technology "k" (PTkt) and the corresponding material intensity of element "i" (IMik).

BLUES results for electric mobility sectors were originally provided in passenger-kilometers (pkm) and tonne-kilometers (tkm). To integrate these figures into the calculation of material demand, they were converted it into vehicle stock, considering average vehicle mileage, typical occupancy, and replacement over time.

Following the conversion, the equation was adapted to represent the additional vehicle stock and include specific technical parameters - such as average battery capacity, electric motor power, and fuel cell characteristics - resulting in Equation 2:

$$DM_i = \sum_t \sum_j \sum_k (CI_{jt} \cdot F_k \cdot PT_{jkt} \cdot IM_{ik})$$

where "Fk" represents the appropriate technical parameters for each technology "k".

Each converter's demand for materials was calculated using data collected from the literature review. The parameters shown in Tables 31 and 32 reflect the assumptions and material selections used in the analysis.

Table 31. Material intensity for NMC and LFP batteries (kg/kWh)

	Lithium	Nickel	Cobalt	Manganese	Copper	Graphite	Lead
LLP	0.10	-	-	-	0.45	1	-
NMC - 622	0.12	0.52	0.17	0.18	0.31	0.90	-
NMC - 811	0.10	0.65	0.08	0.08	0.27	0.90	-
NNIC - 955	0.09	0.82	0.04	0.04	-	0.90	-
NMC average (high-nickel)	0.10	0.66	0.10	0.10	0.29	0.90	-
Na-ion	-	0.50	-	0.60	-	-	-
Lead-acid	-	-	-	-	-	-	18.40

Source: Prepared by the authors based on Barlock et al. (2024); Li, Bieker, Sen (2024); IEA (2024); IRENA (2024); Maisel et al. (2024); Walter et al. (2024); Hossain et al. (2020); Nadeem et al. (2019); Spanos, Turney and Fthenakis (2015).

Table 32. Material intensity of proton membrane fuel cells

Materials (kg/kW)		
Platinum	Carbon black	Total PFSA
6.01E-04	7.19E-04	1.76E-02

Source: Prepared by the authors based on Simons and Bauer (2015); Notter et al. (2015); Evangelisti et al. (2017); Miotti, Hofer and Bauer (2017); Usai et al. (2021); Riemer, Duval-Dachary, Bachmann (2023); Mori et al. (2023); Krishnan et al. (2024); Spreafico and Thonemann (2025); Paladin et al. (2025); Stropnik et al. (2019).

Table 33. Material intensity of permanent magnets (NdFeb)

Characteristics	Material intensity (kg/kg)
Aluminum	0.53%
Boron	0.89%
Cobalt	2.04%
Copper	0.17%
Dysprosium	3.33%
Gadolinium	0.19%
Gallium	0.38%
Iron	63.12%
Manganese	0.23%
Neodymium	22.79%
Nickel	2.03%
Praseodymium	2.76%
Silicon	0.76%

Based on this data, the material demand results in this study are limited to the elements listed in the table below.

Strategic Materials			
Neodymium	Copper	Tellurium	Cobalt
Praseodymium	Lithium	Selenium	Nickel
Silver	Graphite	Gallium	Dysprosium
Silica	Lead	Indium	Boron
Cadmium	Manganese	Platinum	-

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