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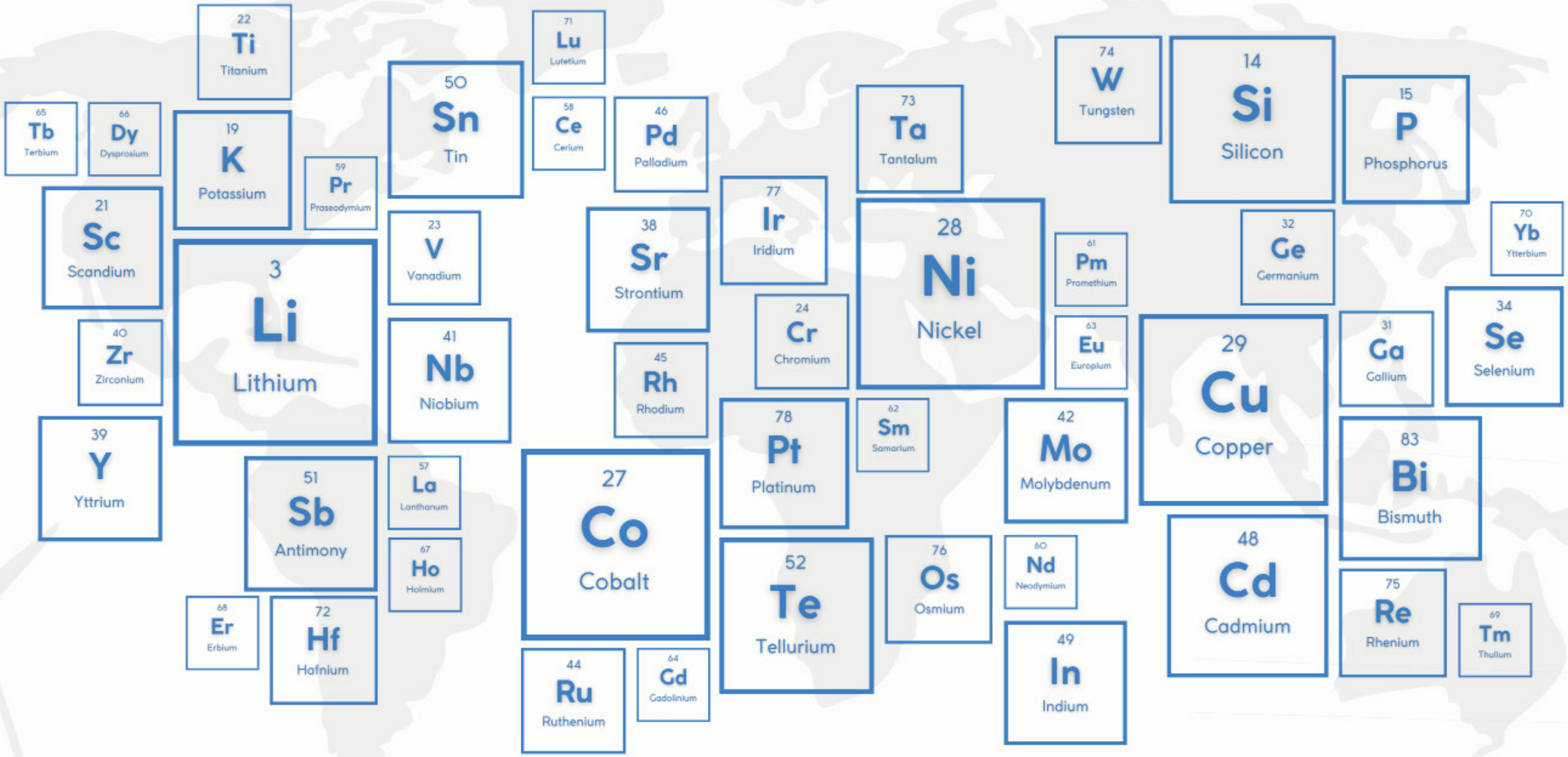
STATE OF THE SECTOR

CRITICAL ENERGY TRANSITION MINERALS FOR INDIA



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Disclaimer

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Organisations

Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. The Council uses data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources.

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SIX PRIORITY METALS: SUPPLY CHAINS, RECYCLING, ESG AND MORE

1 SIX PRIORITY METALS: SUPPLY CHAINS, RECYCLING, ESG AND MORE

The resilience and sustainability of supply chains are critical considerations in today's global economy, especially as industries and governments strive to meet ambitious environmental targets such as Net-Zero Emissions.

This volume aims to provide a detailed understanding of the various factors affecting the supply and demand of the six priority critical energy transition minerals (CETMs) selected for this study: copper, lithium, manganese, nickel, and neodymium. In particular, it covers:

1. **Production & Reserves**: Analysing the global distribution of production sites and known reserves for each metal, including the capacity and lifespan of major mines.
2. **Processing**: Examining the methods and technologies used in the extraction and refinement of these metals, and their respective efficiencies and environmental impacts.
3. **Supply Challenges**: Identifying the primary obstacles faced by leading producers, such as logistical issues, regulatory hurdles, and environmental concerns.
4. **Geopolitical Dynamics**: Exploring how international relations, trade policies, and regional stability influence the supply chains of these metals.
5. **Key Players in the Supply Chain**: Providing details of major companies and countries involved in the mining, processing, and distribution of each metal.
6. **Market and Pricing**: Investigating the factors driving market demand and price fluctuations, including economic trends, technological advancements, and shifts in consumer behaviour.
7. **Recycling**: Assessing the current state of metal recycling, the technologies employed, and the potential to reduce dependency on raw mineral extraction.
8. **ESG Issues**: Evaluating the environmental, social, and governance (ESG) challenges and initiatives within the supply chains, emphasising the efforts to enhance sustainability and ethical practices.

2

COPPER

2 COPPER

2.1 Natural Occurrence

Copper is one of the earliest metals used by humans. It has played diverse historical roles, from casting coins to its crucial modern applications in electrical equipment for wiring, motors construction, electronics, and renewable energy. Its unique chemical properties, including malleability and ductility, enable it to be formed into thin sheets and drawn into fine wire, making it indispensable for clean energy transitions.

Copper is typically extracted via open-pit or underground mining methods. In its natural state, copper exists in two oxidation states ($Cu2+$ and $Cu+$), with isotopes like 63Cu and 65Cu. However, the primary copper ores are chalcopyrite and bornite, which are processed into copper metal through methods such as smelting, leaching, and electrolysis.

2.2 Resources

Substantial copper resources have been identified beyond current production and economically viable reserves. As of 2015, global copper deposits contained 2.1 billion tonnes of copper, with undiscovered resources estimated at around 3.5 billion tonnes (USGS 2023). In 2022, copper exploration budgets increased by 21 per cent to $2.79 billion, the highest level since 2014, primarily driven by high market prices (S&P Global 2022a). However, this increase in exploration spending has not resulted in significant new discoveries in recent years. Consequently, the industry continues to focus on older, established deposits, particularly in Latin America. Chile and Peru have accounted for 43 per cent of the global copper found since 1990 (S&P Global 2023).

2.3 Production & reserves

Copper production has expanded rapidly to meet rising demand driven by economic growth in emerging and developing economies. In 2022, 250 mines operating across nearly 40 countries produced 22 million metric tons (Mt) of copper, marking a 30 per cent increase from a decade ago (USGS 2023). This surge in demand is largely due to copper's unrivalled electrical and thermal conductive properties, which are essential for electrification and the energy transition. The geographical diversity of copper production is broader than that of other CETMs. In 2022, the top four producing countries were Chile (24% of global production), Peru (10%), Democratic Republic of Congo or DRC(10%), and China (9%). The rapid increase in copper production in the DRC in recent years threatens to surpass Peru as the world's second-largest copper producer. Despite a decline in the average copper ore grade in recent years, Chile remains the world's largest producer and holds a fifth of the global economically recoverable copper reserves (USGS 2023). Australia and Peru each hold around 10% of global reserves.

Table 1: Copper Production and Reserves

Country	Mine Production		Reserves
	2021	2022	
Australia	813,000	830,000	97,000,000
Indonesia	731,000	920,000	24,000,000
China	1,910,000	1,900,000	27,000,000

Country	Mine Production		Reserves
	2021	2022	
Russia	940,000 (est.)	1,000,000	62,000,000
Chile	5,620,000	5,200,000	190,000,000
Canada	550,000	530,000	7,600,000
United States of America	1,230,000	1,300,000	44,000,000
Congo (Kinshasa)	1,740,000	2,200,000	31,000,000
Germany	-	-	-
Japan	-	-	-
Kazakhstan	510,000	580,000	20,000,000
Korea, Republic of	-	-	-
Mexico	734,000	740,000	53,000,000
Peru	2,300,000	2,200,000	81,000,000
Poland	391,000	390,000	30,000,000
Zambia	842,000	770,000	19,000,000
Other countries	2,850,000	3,400,000	200,000,000
Total	21,200,000	22,000,000	890,000,000

Source: (USGS 2023)
Data in metric tonnes.

2.4 Processing

The goal of copper processing is to transform mined copper ore, which contains less than 1% copper, into refined copper sheets, or copper cathodes, with over 99% purity. There are two primary types of copper ore: copper sulphide, which accounts for approximately 80% of production, and copper oxide, which makes up about 20%.

Copper Sulphide Processing: Sulphide ore is crushed and ground to produce a concentrate. The concentrate undergoes smelting and electrorefining, often exported to countries like China, to produce refined copper.

Copper Oxide Processing: Oxide ore is treated through a hydrometallurgical process involving solvent extraction and electrowinning, typically conducted near mining sites. The depletion of less capital-intensive oxide ore bodies has led to a 44% increase in the processing of sulphide ores over the past decade (McKinsey 2023a).

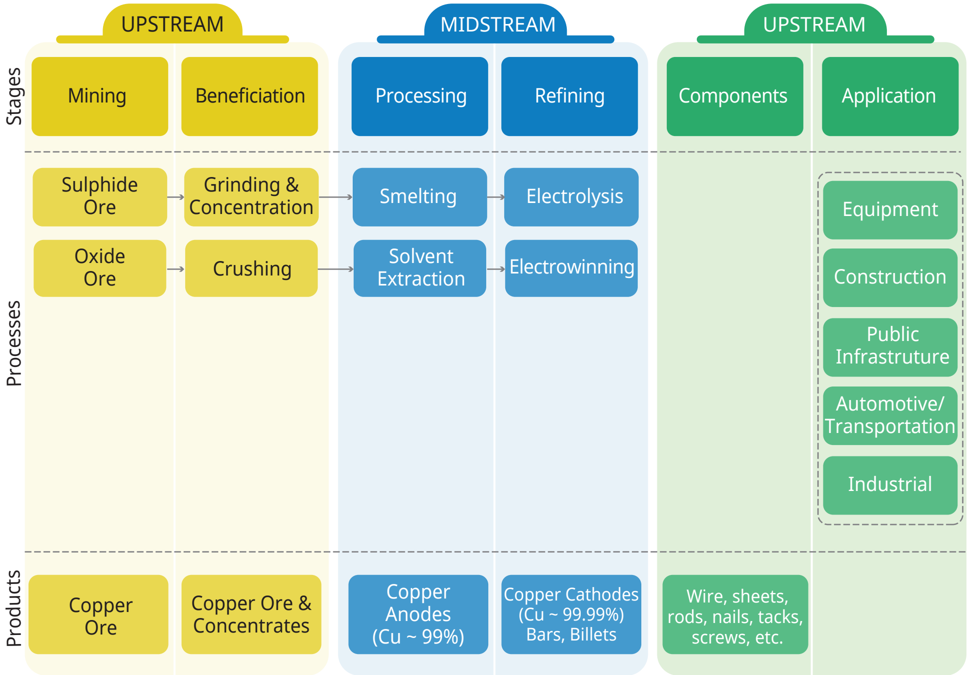
Global Copper Refining: China is the largest copper refining nation, accounting for 42% of global refined copper production. Chile and Japan follow with 8% and 6% of the market share, respectively (Statista 2023). The United States produces 4% of refined copper, relying heavily on imports to meet its demand. China's dominance in copper processing is expected to grow, driven by its substantial share of global refined copper consumption, which rose to 54% in 2021. The United States, the second-largest consumer, accounts for 7% of global usage. There are some early signs of geographical diversification with some of the planned additions to copper processing capacity in the coming years expected in India and Indonesia but new investments in copper smelters continue to be led by China despite concerns around declining treatment and refining charges (Statista 2023; Pickens et al. 2024).

2.5 Extent of value addition in midstream stages

Compared to lithium, copper has a more diversified and mature market with participation from multiple countries across the global value chain. In the midstream stage, smelting remains a primary method for copper ore beneficiation. However, advancements in solvent extraction – electrowinning (SX-EW) have made it possible to efficiently process previously uneconomic ore bodies (Carlson and Le Capitaine, n.d.). Consequently, SX-EW technology has become a cornerstone of the copper industry and is widely used.

Refined copper is shipped to fabricators, who melt it to produce semi-finished copper and copper alloy products, such as wire, rod, tube,

Figure 1: A simplistic representation of the value chain stages of copper



Source: Authors' representation based on (Bamber and Fernandez-Stark 2021)

sheet, plate, strip, castings, and powder. These semi-finished products are then further processed by downstream industries to create end-use products, including cables, connectors, electric motors, transformers, and photovoltaic panels (International Copper Association 2023).

In terms of value addition, copper concentrates (containing around 26% copper) are converted into copper cathodes with 99.7-99.9% purity during the midstream stage, where the maximum value addition occurs. Miners pay treatment charges (TC) and refining charges (RC) to smelters for processing the copper concentrate into refined metal, offsetting the cost of the ore (Liu and Nguyen 2022). TC/RCs are therefore a crucial revenue source for smelters.

2.6 Manufacturing and Use

Copper's superior electrical conductivity makes it an essential material for the energy transition, with use in renewable power generation (e.g. wind, solar photovoltaic) and the electrification of energy end use (e.g., heat pumps, electric vehicles), all of which use substantial amounts of copper (International Copper Association 2023). The International Copper Association projects global copper demand to more than double by 2050, with recycling playing an increasingly important role in meeting demand under a net zero emissions scenario (International Copper Association 2023). In a net zero emissions scenario, total copper demand is expected to increase to 67 million tonnes by 2050. In an optimal scenario, an end-of-life recycling rate of 25 percent could be achieved by 2050, reducing annual demand for primary copper sources by an additional 3 million tonnes (International Copper Association 2023).

2.7 Supply Challenges and Growth Prospects for Leading Producers

Chile: As the world's top copper producer with the largest reserves, Chile experienced a 5.4% production drop in 2022 due to declining ore quality, peak production concerns, and operational issues. Codelco, the state-owned entity, reported a 10.6% decrease in production from 2021, continuing a trend of flat production since 2014. Ore concentrate grades have declined by 30% since 2005, and production at La Escondida, the world's largest copper mine, has peaked. Maintaining and expanding production will require significant investment due to aging deposits and decreasing ore grades. The Chilean Copper Commission (Cochilco) estimates over $70 billion is needed between 2022 and 2030.

Regulatory uncertainty and an outdated concession system are hindering sector expansion, with concession holders not obliged to develop the minerals or make investments, resulting in a low exploitation rate of the country's concessions. Changes to this concession system are expected from 2024, through the establishment of investment targets and revoking concessions for holders that fail to develop them. In May 2023, Chilean lawmakers approved a new mining royalty bill, including an increase in the tax rate on large copper producers that will dedicate a third of raised funds for social programs but may threaten the appeal of new investments (Cambero 2022).

The latest Cochilco forecast projects an increase in Chile's copper production by 17% by 2033, lower than the previous forecast, and delays the copper production peak until 2030, reflecting the slow progress in major mining projects during the COVID-19 pandemic. Codelco recently closed one of its seven copper smelters, located in Ventanas, after decades of pollution incidents in Quintero Bay. On a positive note, the industry is making strides towards sustainability. Chilean copper producers have substantially increased the share of renewable electricity use to almost 50% and source 30% of their freshwater use from the sea. With 40% of Chile's expected 2030 copper production dependent on the execution of the $70 billion portfolio outlined by Cochilco, balancing investment friendliness with environmental, social, and political concerns will be fundamental to ensuring Chile's continued role as the leading copper supplier amid rising demand for the energy transition.

Peru: Peru, faced political, social unrest as well as workers protest in 2022 and 2023, disrupting major mine operations like Las Bambas. This volatility, along with economic challenges, has hindered production growth and investment. Regulatory changes are unlikely in the short term due to political instability. Moody has downgraded its outlook for Peru's sovereign debt from stable to negative, in light of a potential recession in the horizon. Given the uncertain political outlook, structural changes to the mining law are unlikely in the near term to avoid further opposition. Increasing ESG standards and criteria will make it harder to obtain social license to operate new mining projects, in addition to existing restrictions to operations on or adjacent to protected areas and natural reserves, and prior consultation requirements, which are likely to expand, particularly in indigenous lands. Despite the uncertain political landscape and the sluggish performance of the Peruvian copper sector, (production decrease by a CAGR of 1.5% between 2016 and 2021) production is expected to grow at a 6.2% CAGR between 2022 and 2026, driven by large projects like Rio Tinto's La Granja and substantial Chinese investment by Chinese firms, which are expected to invest over $10.2 billion over the next decade in copper projects in the country.

Democratic Republic of Congo (DRC): The DRC, Africa's largest copper producer, saw a 15% production increase in 2021 and holds the second-largest reserves globally. Key players include Glencore, CMOC Group, Zijin Mining, and China Minmetals.. Mining is regulated by the New Mining Code adopted in 2018. Despite export restrictions in 2022-2023 due to royalty disputes, the DRC is expected to see continued growth at a 3% CAGR, supported by projects like Kamoa-Kakula and Mutanda. However, copper production in DRC also faces challenges. From July 2022 until April 2023, CMOC Group faced export restrictions from its copper-cobalt mine in DRC amidst a disagreement on royalty payments with the state-owned mining company Gécamines (Mining Technology 2023).

China: The fourth-largest producer, accounting for 9% of global production, is also the largest consumer and is expanding its smelting capacity to reduce import reliance (USGS 2023). Chinese companies are increasingly investing in international projects. China is the world's largest copper consumer and has a dominant player in smelting and refining, and has announced ambitious plans to further increase its smelting capacity to reduce its reliance on copper cathode imports.

United States: Producing 6% of global copper, the US relies on imports for over half of its refined copper needs. With only three copper smelters in operation, is expected to continue relying on imports for over half of its refined copper requirements over the next decade, exposing it to risks from China's market influence Significant undeveloped projects include Northern Dynasty's Pebble in Alaska and Rio Tinto and BHP's Resolution copper project in Arizona, with over 54 million metric tonnes of combined resources, but new investments face environmental and legal challenges.

Russia: Following the invasion of Ukraine, Russia has lost key European markets and now relies on China as a major buyer, likely at discounted rates despite the looming supply shortfall. Over 50% of its copper exports went to Germany, Netherlands and Turkey. Similar to its oil and gas exports, Russia is likely to rely on China as a buyer of last resort for its copper production (Barich 2022).

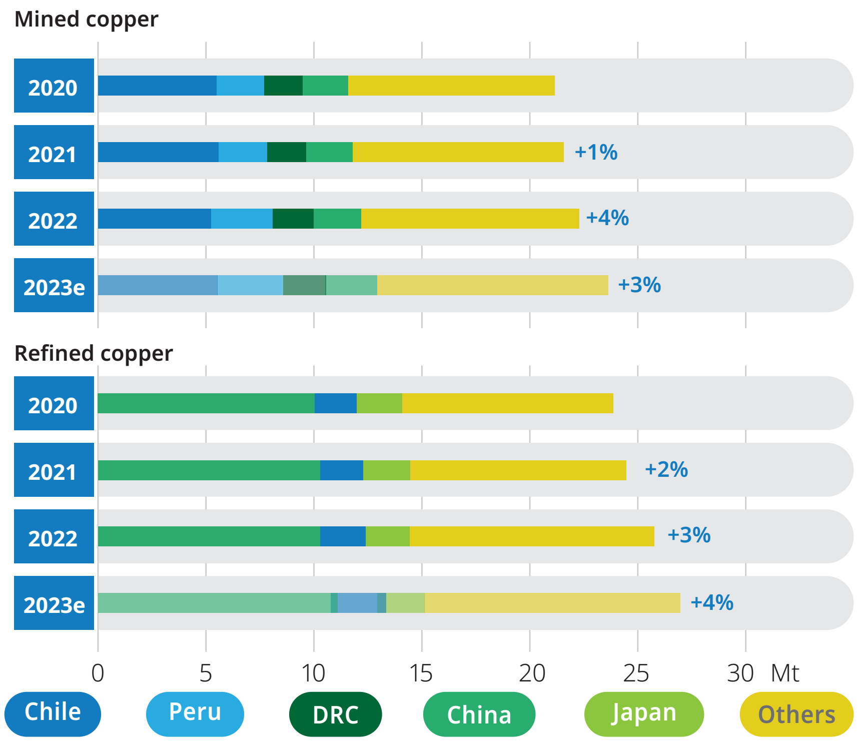
2.8 Investments in Mining and Processing

As seen in Figure 2, Chile continued to remain the top copper-producing country in 2022, with a total output of around 5 million metric tonnes, followed by Peru according to the US Geological Survey. However, copper is not necessarily smelted or refined where it is mined. Mainland China accounts for 36% of smelting and 35% of refining capacity respectively (and an even higher share for actual smelting/refining), despite making up just 7% of mined copper capacity (S&P Global 2023).

Estimates show that refined copper capacity in China increased by about 1.2 million tonnes in 2018 to 12.2 million tonnes. New capacity came online at a minimum of seven refineries in the country, either through the opening of new facilities or upgrades at existing facilities. Most notably, Chinalco Southeast Copper Co., Ltd. finished construction of a new refinery with an annual cathode production capacity of 400,000 tonnes, and Guangxi Nanguo Copper Co. completed a 300,000 tonnes per year expansion (Indian Bureau of Mines 2022).

Copper also remained one of the metals that witnessed high Merger and Acquisitions (M&A) activities in the last few years. Rio Tinto's acquisition of Turquoise Hill Resources (USD 3.1 billion), which included Mongolia's Oyu Tolgoi mine, was a notable example. BHP's acquisition of OZ Minerals

Figure 2: Growth trend in refined copper over the last four years



Source: (IEA 2023)

(USD 6.4 billion), which was completed in May 2023, is another example (IEA 2023).

2.9 Key companies involved in the supply chain

The largest copper-producing companies in 2022 included Codelco (Chile) with 1,522 kilotonnes, marking a 10% decline from 2021, and Freeport-McMoRan (USA), which produced 1,297 kilotonnes, a 7% increase from the previous year. BHP Group (Australia) followed with 1,108 kilotonnes, up by

6%, while Glencore (Switzerland) saw a 17% decrease to 993 kilotonnes. Southern Copper (Mexico) produced 895 kilotonnes, a 7% drop from 2021, and First Quantum Minerals (Canada) remained steady with 741 kilotonnes. Zijin Mining (China) experienced significant growth with 677 kilotonnes, a 42% increase. KGHM Polska Miedz (Poland) saw a slight decline of 4% to 537 kilotonnes, while Rio Tinto (Australia) produced 521 kilotonnes, up by 5%. Anglo American (UK) reported 468 kilotonnes, a 1% increase from 2021.

These top 10 companies produce around 50% of the world's copper supply, with production well distributed, reducing single-source risk. Notably, 9 out of these 10 companies are based in OECD countries with developed mining regulations.

Codelco remains the world's top copper producer despite challenges such as declining ore quality, water restrictions, and union protests. Other major producers like Freeport-McMoRan and Southern Copper have also faced disruptions due to environmental and social issues. Joint ventures and mergers have become common, with notable examples including PolyMet and Teck American's JV in Minnesota. Joint ventures are also seen as a way to unlock stalled copper projects in Peru. In 2022, the industry saw 18 copper-focused M&A deals for a total of over USD 14.2 billion, with 10 of them targeting assets in the development stage, reflecting long-term strategies to increase reserves in view of the expected market deficit caused by increased energy transition-related demand. Significant deals include BHP Group's proposal to acquire OZ Minerals Ltd for USD 5.94 billion increasing its exposure to copper assets in South Australian copper basin and Rio Tinto's acquisition of Turquoise Hill Resources Ltd for USD 3.1 billion including the expansion stage of the world-class You Tolgoi mine in Mongolia (IEA 2023).

Chinese companies are also expanding their global presence to secure raw copper for their smelting industry. Zijin Mining has acquired stakes in major operations such as the Kamoa-Kakula and Kolwezi mines in DRC and the Bor mine in Serbia. Some OEMs are pursuing vertical integration to ensure critical mineral supplies. For instance, Stellantis acquired a 14.2% stake in McEwen Copper, which operates the Los Azules mine in Argentina.

2.10 Pricing and Markets

Copper prices are traditionally seen as a barometer of economic health due to the metal's extensive use in manufacturing, electronics, and power generation and transmission. In recent years, copper prices have surged to record highs driven by anticipated demand growth, tight market conditions and declining ore grades (International Copper Study Group 2023). While copper prices can fluctuate, future supply deficits are expected to provide a high floor for these fluctuations.

The transition to electric vehicles (EVs) and the broader electrification of the economy to achieve net-zero emission goals will significantly increase copper demand. S&P Global estimates an 82% growth in copper demand from 2021 to 2035. Recent investments in large projects in Peru, the Democratic Republic of Congo (DRC), and expansion projects in Mongolia are expected to boost near-term supply (S&P Global 2022c). However, the declining medium-to-long-term project pipeline, long lead times for new projects, and concerns about peak production at major mines are likely to result in a copper deficit due to the strong demand growth associated with the energy transition. This will lead to tighter markets and price increases.

The International Energy Agency (IEA) estimates a 45% increase in copper demand by 2030, leading to a nearly 20% supply deficit, equivalent to 6 million metric tonnes (Mt), under its Net Zero Scenario. Even in the less mineral-intensive Announced Pledges Scenario (APS) , a copper supply deficit of around 5% is expected. To meet the projected level of demand in the NZE scenario, copper will require two-thirds of the estimated $360 to $450 billion of cumulative investment, equating to the development of 80 new average-sized mines (International Energy Agency 2023).

S&P forecasts copper demand to double from 25 million tonnes (Mt) in 2021 to nearly 49 Mt in 2035, with half of this growth driven by energy transition technologies (S&P Global 2022a). This represents unprecedented production growth within a relatively short timeframe. Besides expanding production capacity, the extent of this deficit will depend on supply- and demand-side responses to higher prices. These responses include increasing mine capacity utilisation, enhancing copper recycling rates, innovations in processing, and potential demand reduction in non-energy transition sectors.

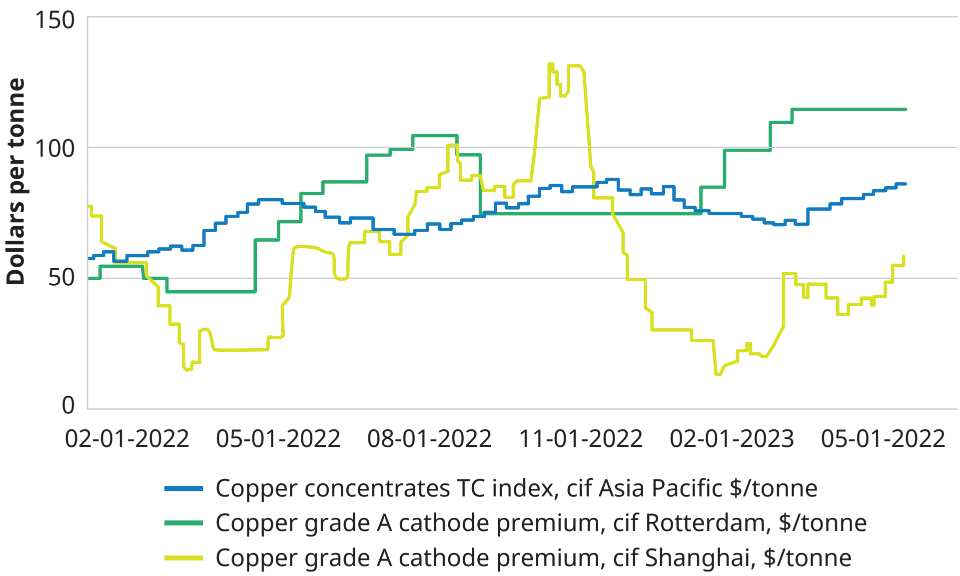
Copper markets have experienced significant unpredictability in recent years due to variable mining rates in countries like the US, China, Chile, and Peru, disrupting global supply chains. Decreasing ore grades in major producers such as Peru and the US have further compounded supply issues, leading to price volatility. For instance, the U.S. Geological Survey reported reduced copper production in 2018 due to lower outputs from mines in Arizona and New Mexico (USGS 2023). Political unrest in key copper-producing nations like Peru and Chile has also contributed to supply shortages, negatively impacting industries reliant on copper, such as electrical equipment and heavy industrial machinery production. In Chile, declining ore quality further disrupts supply chains, adding to price instability. To manage copper price volatility, businesses and investors often use strategies like hedging, portfolio diversification, monitoring global economic trends, and securing long-term supply agreements to stabilize pricing and mitigate risks associated with fluctuations.

Meanwhile, the domestic price of copper in India is linked to the London Metal Exchange (LME) price. The price of MIC2 is derived from the LME price after adjusting for the prevailing TC/RC, which is a market-driven parameter depending on the international supply and demand for copper (Ministry of Mines 2023). TC/RCs increase when there is a higher supply of copper concentrates, strong demand in end-use sectors, and when smelters can negotiate better terms for feedstock. In 2022, Indian copper smelters benefited from higher global supply of copper concentrates, driven by strong domestic recovery due to a push for renewables, urbanisation, infrastructure development, and digitization (Hindalco Industries Limited 2023). This trend is expected to continue in 2023, with benchmark TC/RC set at USD 88 per tonne (22.6 c/lb), approximately 35% higher than in 2022.

Figure 3: Copper Prices

Source: (Trading Economics, n.d.)

Figure 4: Recent volatility in global copper prices with high treatment and refining margins



Source: (Fastmarkets, n.d.)

2.11 Agreements and Contracts

Offtake Agreements: Offtake agreements have been crucial in funding and developing copper mining projects in regions with significant resource potential but are not major mining jurisdictions. Alara Resources Ltd., an Australian-based exploration and mining company, has projects in Oman and Saudi Arabia (Alara Resources, n.d.-a). In July 2023, Alara entered an eight-year offtake agreement with Trafigura for its Wash-hi Majaza copper-gold mining project in Oman (Iannucci 2023). The agreement includes three exploration licenses, one mining license, and a copper concentrate plant (under construction) with a future capacity of one million tpa of copper ore. Alara will supply its entire copper concentrate production to Trafigura, with pricing based on the London Metal Exchange at the time of delivery (Alara Resources, n.d.-b). Additionally, Alara secured a USD 3.45 million finance facility from Trafigura, repayable in sixteen equal quarterly instalments by June 2029. The agreement allows Trafigura to convert outstanding dues into Alara shares, capped at 20% of the total shares.

Some offtake agreements include advance payments, providing crucial financing for mining companies before the agreement term begins. In June 2021, CITIC Metal and Zijin Mining entered an offtake agreement with Kamoa Copper for the Kamoa-Kakula mine in the DRC. Each company agreed to purchase 50% of the copper concentrate and blister copper from the mine and the Lualaba Copper Smelter (Mining Technology 2021). This agreement allowed Kamoa Copper to secure a total advance payment of USD 300 million to help finance the project (Ivanhoe Mines 2021). Pre-payment clauses benefit both parties: sellers receive financial support for mine development, and buyers secure their supply chains, as sellers must either deliver the minerals or repay the advance with interest.

Pre-payment agreements are also used in supply chains where minerals are processed for end-use. Austral Resources in Australia produces copper cathodes at its Anthill project, which has a copper ore reserve of 5.06 Mt. In early 2022, Austral entered an offtake and pre-payment agreement with Glencore Plc. Under the agreement, Glencore will have rights to up to 40,000 tonnes of copper cathode from Austral, starting in the second half of 2022 (INN 2022). Additionally, Glencore will provide a USD 15 million pre-payment facility to Austral, repayable over two years from 2022.

Investors and shareholders in mining companies often secure offtake agreements, granting them rights to a significant portion of mine production. This strategy helps procurers ensure resilient supply chains. Chinese companies frequently adopt this approach to gain rights to minerals globally. CITIC Metal, one of the largest global investors in mining, exemplifies this strategy. It controls 80% of the niobium market in China and is the largest shareholder in Ivanhoe Mines, a Canadian company with three major mines

(CITIC, n.d.). Such acquisitions help China maintain its dominance in critical mineral supply chains (CITIC, n.d.).

In July 2014, CITIC Metal acquired a 15% stake in the Las Bambas copper mine in Peru, one of the world's largest copper mines with an annual production of 250,000 tonnes of copper concentrate (MMG, n.d.). In January 2016, CITIC Metal entered a lifetime offtake agreement with Minera Las Bambas, entitling CITIC Metal to 26.5% of the mine's total production (MMG 2016). The agreement specifies that the price of copper concentrate will depend on the copper, silver, and gold content.

Streaming Agreements: Streaming agreements provide vital financing for mining companies (Bourassa 2019), differing from offtake agreements by being long-term and offering diverse funding methods (McKinsey 2021). Buyers make upfront payments for specified commodities over a long period. Often, mining companies use streaming agreements for by-products like gold and silver produced during copper mining to fund their primary operations (Wheaton Precious Metals, n.d.).

In June 2021, Ero Copper Corp, based in Vancouver, entered a streaming agreement with Royal Gold for gold production from the NX Gold Mine in Brazil. Ero Copper focuses on increasing copper production in Brazil through its stake in some of Brazil's largest copper mines (ERO Copper, n.d.). Royal Gold agreed to pay an upfront amount of USD 100 million, with an additional USD 10 million contingent on performance, to purchase gold. This funding supports Ero Copper's copper production projects in Brazil (Ero Copper Corp 2021).

2.12 Recycling

Copper faces a relative supply risk rating exceeding 30%. Globally, copper is among the most recycled metals, retaining its performance qualities through recycling. Over the decade from 2009 to 2018, around 32% of the 26.7 million tonnes of copper used annually worldwide came from recycled sources (International Copper Association 2021). When scrap copper is received for recycling, it undergoes visual inspection, grading, and, if necessary, chemical analysis. Scrap not immediately required is bale-stored.

Number 1 scrap is directly melted, sometimes followed by fire purification for increased purity. Chemical analysis is conducted on the molten copper to ascertain its purity level before casting into intermediate shapes like billets, cakes, or ingots for further processing.

Number 2 scrap, often purified through electrolysis to achieve desired purity levels, may undergo preliminary fire refining before being cast into anodes. This meticulous recycling process ensures that recycled copper meets quality standards for its diverse applications, contributing significantly to sustainable resource management and reducing reliance on primary copper sources.

2.13 Copper Consumption and Production in India

The per capita consumption of refined copper in India during 2019-20 was 0.5 kg, significantly lower than the 10 kg average in developed nations (Indian Bureau of Mines 2020). India's refined copper consumption is forecasted to expand by over 15% from a year earlier to around 620,000 tonnes, with an annual growth rate averaging more than 12% during 2022-2027 (Arora and Nguyen 2022).

India is not self-sufficient in copper ore production to meet its domestic demand. The demand for copper minerals for primary copper production is met through two sources: indigenous mines and imported concentrates. Hindustan Copper Limited (HCL), a state-owned enterprise, is the only primary copper producer involved in indigenous mining. Other primary copper producers in the private sector import the required mineral in the form of concentrate for their smelters (Ministry of Mines 2023). The domestic demand for copper and its alloys is met through domestic production, imports, and recycling of scrap for secondary copper production. In 2021-22, the production of copper ore from five mines (all owned by HCL) stood at 3.57 million tonnes, registering a 9% increase over the previous year. Copper concentrate production increased by 5% to 114 thousand tonnes in 2021-22 compared to the previous year (Indian Bureau of Mines 2022).

The Indian copper refining industry is dominated by three major players: Hindustan Copper Limited (HCL) in the public sector, Hindalco Industries Ltd. , and Sesa Sterlite Ltd (Vedanta Resources Limited) in the private sector (Indian Bureau of Mines 2022). Additionally, M/s Kutch Copper Limited, promoted by the Adani Group, is installing a custom copper smelter refinery complex named Kutch Copper Limited with a capacity of 1 million tonnes in a phased manner. Construction for the first 500,000 tonnes of capacity has begun, and the project is expected to start operating in 2024 (Arora and Nguyen 2022).

Hindustan Copper Limited (HCL) is the only vertically integrated company in India involved in the mining, beneficiation, smelting, refining, and casting of refined copper (Vanshit 2023). Hindalco Industries Ltd. and Vedanta Resources Limited mainly rely on imported copper concentrates and own copper mines in other countries. Their profitability depends on international variations in Treatment Charges (TC) and Refining Charges (RC), but they offset the risk of LME copper price volatility through hedging (Ministry of Mines 2023).

In FY2021-22, Hindalco Industries Ltd. acquired Polycab's CCR unit, Ryker (now Asoj), which can produce 225,000 MT of copper rods (Hindalco Industries Ltd. 2023). This acquisition positioned Hindalco among the world's top 3 copper rod players outside of China. The company is also planning to install a copper and e-waste recycling facility with a capacity of 50 KTPA. Additionally, Hindalco is entering downstream manufacturing with India's first inner grooved copper tubes (IGT) facility in Waghodia, Gujarat, with a planned capacity of 25 KTPA under the Government's PLI scheme for white goods (Hindalco Industries Ltd. 2023).

Given the anticipated exponential demand for copper, India should support its copper refining and downstream manufacturing to maximize value addition. With new entrants in the refining business, the government is exploring ways to forge backward linkages and boost production from mining. The recent introduction of provisions for a new mineral concession, the Exploration Licence (EL), in the Mines and Minerals (Development & Regulation) Amendment Act, 2023, aims to attract private sector investment and boost production (Press Information Bureau 2023c).

The government could also reassess terms with major trade partners for copper ore and concentrate imports. Based on 2022 UN Comtrade data, India's main trade partners for copper ore and concentrates are Chile (36%), Indonesia (24%), Peru (12%), Australia (8%), and Panama (8%). However, ore and concentrate supply from both Indonesia and Panama stands disrupted in 2024 due to the partial export ban imposed by Indonesia in 2024 and the closure of the Cobre Panama mine in Panama (Raizada and Moerenhout 2024). To help domestic smelters, the government in turn eliminated the basic custom duty on copper concentrate and blisters in 2024 to ease supply chain constraints (Ministry of Finance 2024). The government could also adopt China's model of establishing wholly owned or joint ventures with companies in major producer countries and securing long-term supply through FTAs (Renaud, Manley, and Nassar 2023; Wise 2012).

Additionally, the government should encourage refining copper scrap. India has a very high collection rate of end-of-life copper scrap and recycling rate but most of this scrap is directly melted as against refining done in other parts of the world (Copper India 2021). Currently, scrap collection is mainly done by the unorganised sector, and there is limited data on the potential use of secondary copper in the country. The last government estimates date back to 2010, with independent studies estimating significant use of scrap at each stage of the value chain (Indian Bureau of Mines 2022; Renaud, Manley, and Nassar 2023). The government could incentivise smelters, refiners, and fabricators to use scrap through fiscal instruments, reducing import dependence and promoting circularity in the domestic supply chain.

Finally, to support forward linkages, the government should prepare a detailed demand estimation for future copper requirements across multiple end-uses in the country, providing demand certainty for new entrants.

3

LITHIUM

3 LITHIUM

3.1 Natural Occurrence

Lithium (Li), often called "White Gold", is a lightweight and versatile metal that is becoming increasingly important as global efforts to shift transportation from fossil fuels to sustainable energy sources intensify. Lithium-ion batteries are crucial for powering electric vehicles (EVs). The rapid pace adopted by electric vehicle manufacturers to decarbonise the transportation sector has accelerated the global demand for lithium, earning it the nickname "white gold" in the industry. Lithium-ion batteries are favoured for their high energy density, which allows them to store substantial energy in a compact and lightweight form, driving their market demand.

Lithium occurs naturally in two isotopic forms—6Li and 7Li—and is found in various minerals such as spodumene, petalite, lepidolite, and amblygonite. It is primarily extracted from brines in Chile and processed into lithium carbonate and lithium hydroxide.

3.2 Resources

While there are ample lithium resources in the earth's crust, many are not yet economically recoverable. This creates a tight market. despite the geological abundance, as current production is limited and concentrated in a few countries. Essentially, we have enough lithium underground but insufficient production capacity.

Recently, significant lithium discoveries have been made but are yet to be categorised as resources or reserves. Noteworthy examples include Iran's discovery of deposits equivalent to 8.5 million tons of lithium carbonate and India's identification of 5.9 million tonnes of inferred lithium resources (Financial Tribune 2023; Press Information Bureau 2023a).

Table 2: Lithium Reserves

Country	Lithium Resources
Bolivia	21,000,000
Argentina	20,000,000
United States	12,000,000
Chile	11,000,000
Australia	7,900,000
China	6,800,000
Germany	3,200,000
Congo (Kinshasa)	3,000,000
Canada	2,900,000
Mexico	1,700,000
Czechia	1,300,000
Serbia	1,200,000
Russia	1,000,000
Peru	880,000
Mali	840,000

Country	Lithium Resources
Brazil	730,000
Zimbabwe	690,000
Spain	320,000
Portugal	270,000
Namibia	230,000
Ghana	180,000
Finland	68,000
Austria	60,000
Kazakhstan	50,000
World Total	98,000,000

Source: (USGS 2023).
Data in metric tonnes.
(USGS estimates do not yet include recently discovered deposits in India)

3.3 Production & Reserves

Lithium production is highly concentrated, with 90% coming from Australia, Chile, and China. The majority of global lithium production is accounted for by six mineral operations in Australia, one mineral tailings operation in Brazil, two brine operations each in Argentina and Chile, and three mineral and two brine operations in China (Azure Minerals Limited 2024). These countries also possess most of the economically viable reserves.

There are two primary types of lithium operations: brine and mineral rock. Lithium from brines is often processed into lithium carbonate, which is used in EV batteries but is less suitable for high-nickel content batteries that offer higher energy densities and longer driving ranges. These premium batteries typically require lithium hydroxide, which is more easily processed from hardrock lithium.

Table 3: Lithium Production and Reserves

Country	Mine Production		Reserves
	2021	2022	
Australia	55,300	61,000	6,200,000
Chile	28,300	39,000	9,300,000
China	14,000	19,000	2,000,000
Argentina	5,970	6,200	2,700,000
Brazil	1,700	2,200	250,000
Canada	N/0	500	930,000
United States of America	N/A	N/A	1,000,000
Zimbabwe	710	800	310,000
Portugal	900	600	60,000
Other countries	N/0	N/0	330,000
Total	107,000	130,000	26,000,000

Source:(USGS 2023).
Data in metric tons.
N/A represents US production that is withheld to avoid disclosing company proprietary data
N/0 represents negligible or zero

Australia: Australia's outlook is positive due to its stable regulatory environment, efficient permitting process, and strong political support for increasing lithium production. As the largest producer of lithium, primarily from spodumene in Western Australia, Australia accounted for about one-fifth of global lithium production in 2021. The Greenbushes mine, a key site, received permission in 2019 to double its size. Australia's current priority is to expand its processing capacity, and the government has allocated USD 1.5 billion for lithium processing projects, capitalising on the easier conversion of spodumene to lithium hydroxide. Proximity of production to refineries also reduces transport costs, and the resulting products can benefit from US Inflation Reduction Act subsidies. However, challenges include the higher emissions intensity of hardrock lithium mining compared to brine operations, public backlash due to pollution concerns (production leads to sulfuric acid and waste as well as mixing of metal with water flows during rainfall), and operational issues such as sourcing skilled labour and avoiding cost overruns and delays.

Chile: Chile holds a prime position for increasing lithium production, with the Atacama salt flats having the highest lithium density globally. Its brine operations are low in emissions and freshwater usager. Besides the Atacama desert, Chile has 18 other salt flats with lithium potential. The country produces about 61% of global lithium carbonate, essential for lithium iron phosphate (LFP) cathodes, and its processing plants can scale up as more brine becomes available.

Chilean production suffers more from political and popular challenges than technical ones. On the political side, in April 2023, Chile's government announced a nationalisation strategy for its lithium industry. The strategy was engrained with poorly defined concepts and there remains a lack of clarity on what role the state will play. The state-owned copper company Codelco is also renegotiating the current contract of Sociedad Química y Minera de Chile SA (SQM), which holds all the assets of the current field. Since their contract is to expire in 2030, there is little incentive for SQM to invest in their fields before they have an agreement on a contract extension. At the time of writing, the process to attract new players and open new lithium fields, as well as the process of negotiation a majority share for the state in existing operations remains unclear. After Chile's lithium nationalisation plans, the stocks of Australian lithium miners increased. The country also has serious concerns from local communities about the benefits they capture, as well as from environmental groups.

China: China plans to become the world's second-largest lithium producer, overtaking Chile within the next five years. The government supports new lithium mining capacity development to reduce import reliance, with 24 projects underway. Although half of China's current production is from brines, future projects will focus on hard rock mining. Despite these plans, China faces challenges, such as insufficient domestic reserves to meet demand, leading to continued reliance on imports. In 2021, China imported 90% of its lithium from Australia. Domestic resources are often low grade and scattered, complicating extraction and increasing environmental harm. Illegal mining also presents challenges, and crackdowns could reduce domestic supply. For example, its resources in Jianxi (and some other provinces) have a low lithium grade and are more difficult and environmentally harmful to extract. Additionally, China has a lot of illegal mining and crackdown on those practices may reduce domestic supply of lithium.

United States: North America is investing heavily in lithium exploration, with production projected to grow from 1% to 10% of global production this decade. Government incentives, including Department of Energy loans, support this expansion.

Bolivia: Bolivia, with the largest lithium resources globally, signed a $1 billion agreement with Chinese firms in 2023 to apply Direct Lithium Extraction (DLE) methods (Wischer and Villasmil 2023). However, significant lithium production has yet to begin.

Argentina: Argentina, known for its investor-friendly environment and low royalty rates, is set to surpass Chilean production by the end of the decade (2030), attracting substantial foreign direct investment in several projects.

Zimbabwe: Zimbabwe is emerging as a significant player in the global lithium market. The country possesses substantial lithium reserves and has been ramping up its production efforts in recent years. Zimbabwe is home to some major lithium mining projects, notably the Bikita Mine. Zimbabwe has implemented bans on raw lithium exports to promote domestic processing. Such restrictions are designed to encourage the development of local processing industries (ESI Africa 2023).

3.4 Processing

Lithium can be found in sources like brine deposits, mineral ore, clay, seawater, and geothermal well. Globally, two primary resources exist for extracting lithium hard rock (spodumene) and brine. Hard rock is the most commonly used source for lithium extraction, accounting for 60% of the global mined lithium supply (Benchmark Source 2023). Hard rock mining of lithium has often been criticised for its vast environmental footprint as this form of extraction emits significant amounts of greenhouse gases, requires larger quantities of water, and produces toxic waste (C. A. Williams 2022).

The second most commonly used resource for lithium extraction is brine. Lithium is extracted from liquid brine reserves underneath salt flats known as Salars (SAMCO Technologies, n.d.). Most of the world's exploitable lithium reserves are in salt-lake brine found in the United States of America, China, Chile, Argentina and Bolivia. Brines are found in salar dips under the ground, and the brine content is pumped out to the surface. Due to the very dilute nature of lithium concentrates, brines are further solar evaporated in large ponds. Brine remains in these ponds longer to reach the optimal lithium concentration level for further processing. While the evaporation method is the most commonly used method of extracting lithium, it too has been criticised for its vast environmental impact. Regions with large-scale salar ponds, such as Salar de Atacama, require large land regions and divert any available water, impacting the water availability for communities in the region (Cleantech Lithium, n.d.).

Direct Lithium Extraction (DLE) is a fast-growing technology in lithium extraction that aims to address the environmental and lead time concerns with other prevalent methods. DLE technology uses filers, membranes and other equipment to recover lithium directly from the brine without needing large evaporation pounds. The DLE method is regarded as the step towards green lithium extraction as it requires less water consumption, and brine is reinjected back into the basin aquifers (International Battery Metals, n.d.). DLE is a promising technology for increasing the lithium supply shortly, but most projects still use the evaporation method. 27 projects globally are using or planning to invest in DLE technologies as there is a push towards addressing ESG concerns associated with lithium extraction.

Approximately 60% of global lithium processing capacity is located in China. Chile and Argentina process around 29% and 10%, respectively, where lithium from brines is directly converted into lithium carbonate domestically (Goel et al. 2023). The EU and US have minimal lithium refining capacity, and despite being the largest producer of lithium, Australia processes very little. However, Australia's 2022 Critical Minerals Strategy aims to expand downstream processing.

Looking ahead to 2032, China is expected to maintain its dominance in lithium chemical production. While the US and Australia will see the most significant percentage growth in processing capacity, China will more than triple its current capacity and retain far more than half of lithium processing by the end of the decade (Goel et al. 2023).

Table 4: Lithium Processing

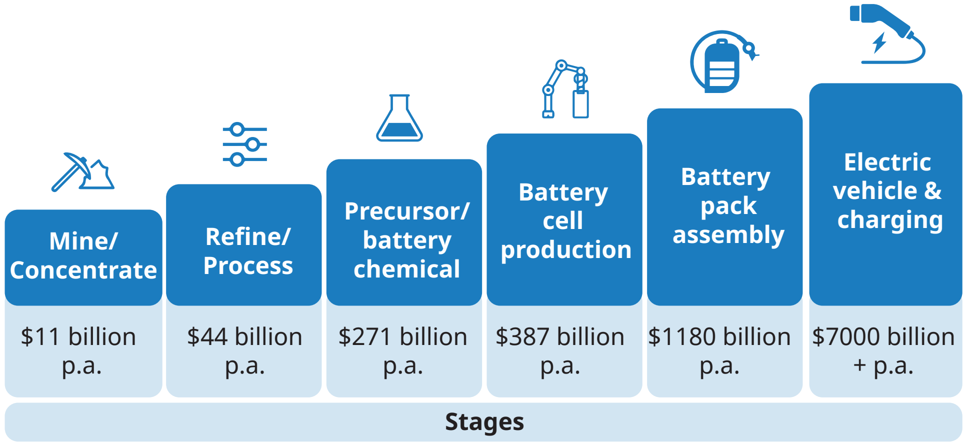
Country	Processing % of world
China	58
Chile	29
Argentina	10

Source: (International Energy Agency 2021)

3.5 Extent of value addition in midstream stages

Lithium is a specialised chemical rather than a standardised bulk commodity like copper or iron (Goel et al. 2023). It is primarily used in low-carbon technologies (LCTs), with battery storage accounting for 74% of its end-use consumption in 2021 (International Energy Agency 2021). By 2035, estimates show that the global value of processing and refining sector for the global lithium-ion battery value chain could be around USD 44 billion per annum (see Figure 5) (Department of Industry, Science and Resources, Commonwealth of Australia, 2022).

Figure 5: Projected global value of lithium-ion battery value chain for 2035

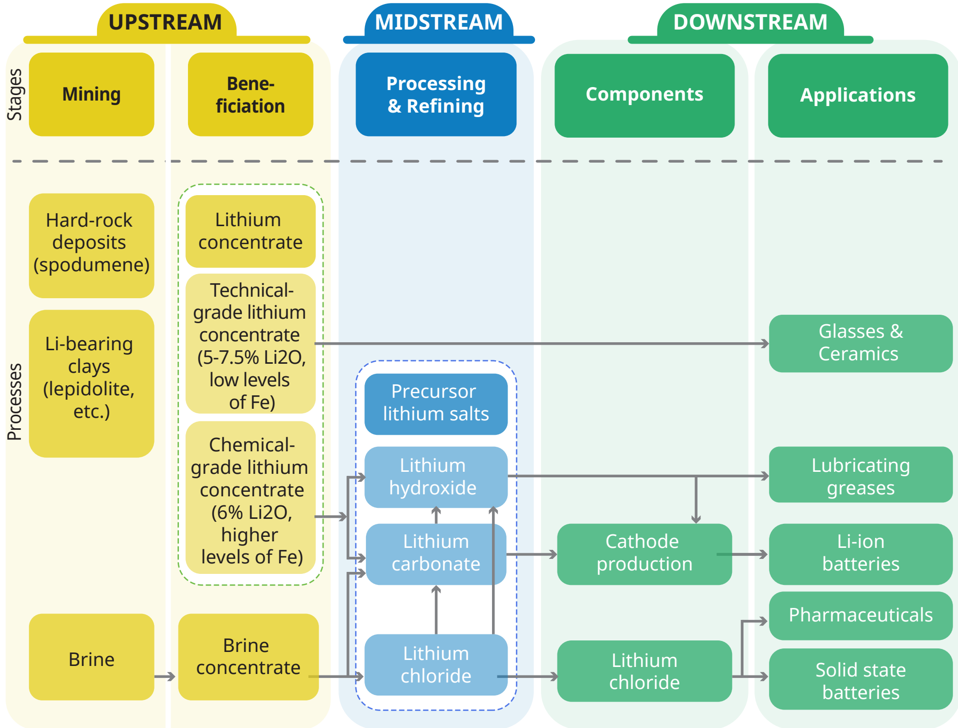


Source: (Department of Industry, Science and Resources, Commonwealth of Australia, 2022)

The two commercial lithium compounds for LCTs are high purity 'battery grade' lithium carbonate (Li_2CO_3) and lithium hydroxide monohydrate ($LiOH.H_2O$). The choice between them is usually determined by what type of lithium battery is going to be produced (Goel et al. 2023). Ordinary nickel manganese cobalt (NMC) cathode materials (NMC111, NMC442, NMC532, NMC622) and LFP battery tend to use lithium carbonate, while Ni-rich NMC811, NCA and select LFP cathode materials preferably use lithium hydroxide (Huang et al. 2020).

As seen in Figure 6, these precursor lithium salts – namely lithium carbonate, lithium hydroxide and lithium chloride are produced using different extraction and refining techniques based on their mineral resource. The current lithium production is based on three types of resources, namely brine (~64%), pegmatite-type (hard-rock) (~29%), and clay-type (~7%) (Zhao, Wang, and Cheng 2023). Hard rock-based ore mineral ("spodumene" which may contain 1-4.2% Li_2O) is converted into spodumene concentrates (6% Li_2O in case of chemical-grade) using gravity, heavy media, flotation and magnetic processes (Huang et al. 2020). The spodumene concentrate is then fed into the chemical plants or convertors for further processing and production of various precursor lithium chemicals, the vast majority of which currently are in China. In case of continental brines, lithium extraction is done using open air evaporation to concentrate the brine. This is an intrinsically slow process but there are some direct lithium extraction (DLE) methods that are also currently under experimentation (Vera et al. 2023).

Figure 6: A simplistic representation of the value chain stages of lithium



Source: Authors' representation based on(Hao et al. 2017; Zhao, Wang, and Cheng 2023)

Since the production process for lithium concentrates differs based on their mineral resource, the resulting production costs also vary. Lithium hard-rock operations typically cost lower than brines (S&P Global 2019). However, the price hard-rock producers receive for their end-product, usually spodumene concentrate, is significantly lower than that received for lithium carbonate, chloride and hydroxide, which are produced at brine operations (S&P Global 2019). Therefore, for countries with hard-rock deposits (such as Australia and now potentially India), value capture at the processing and refining stage can be critical.

The current volatility in lithium prices makes it challenging to precisely gauge the value added at the midstream processing level for merchant refiners. Nevertheless, projections and recent studies suggest that the value addition for the lithium processing and refining sector could range from 8% to 37%, with the lower end based on conservative price estimates and the upper end reflecting the exceptional prices seen in 2022(with 8% based on conservative prices and 37% based on 2022 prices). It's worth noting that contrary to common perception, the primary cost driver is not mining but the availability of processing infrastructure, even with the higher conversion margins (Ewing and Krauss 2023).

3.6 Investments in Mining and Processing

There has been a significant increase in investments in lithium mining. In 2022, global investment in lithium mining projects surged to $4.67 billion, up from $1.93 billion in 2021. This upward trajectory is anticipated to persist in the foreseeable future as lithium demand continues to escalate.

The majority of investments in lithium mining are being directed towards projects in Australia, Chile, and Argentina, which collectively hold the world's largest lithium reserves. From 2020 to 2022, Chinese companies have invested a staggering $4.5 billion to acquire stakes in nearly 20 lithium mines, predominantly located in Latin America and Argentina (Hua and Wexler 2023).

Table 5 provides insight into the diverse array of projects that have invested in lithium processing plants, with variations based on geographical location, mining methods, setup costs for processing plants, and the proportion of processing costs in the initial capital outlay for plant establishment. The development cost of an average lithium project, including both mining and processing units, typically exceeds one billion dollars, yet this expense varies depending on factors like geographic location, lithium source (hard rock or brine), mining and processing site area, and production capacity, as illustrated in Table 5.

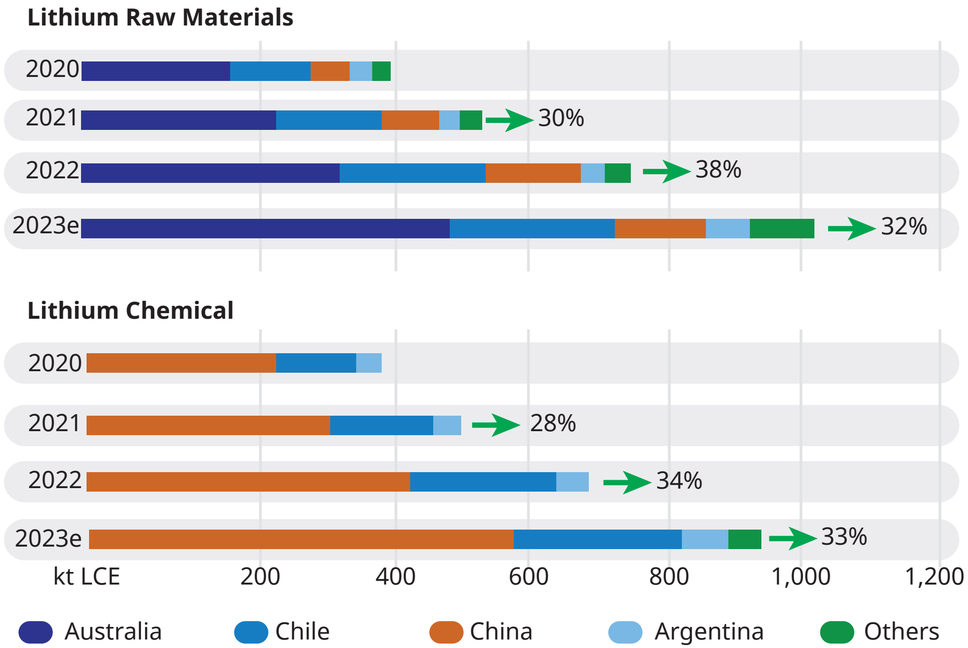
Table 5: Varying costs of setting up lithium processing plant at various sites globally (2022 data)

Project Name	Owners	Country	Mining Method	Processing plant cost ($M)	Share of initial capital cost (%)	Hydroxide conversion plant cost ($M)	Hydroxide plant capacity
Piedmont	Piedmont Lithium Inc. (100% owner)	United States (North Carolina)	Open pit	615	62	408	30,000 t/y LiOH
Karibib	Lepidico Ltd. (Venturer) 80% Private interest venture 20%	Namibia	Open pit	112	72	85	5,600 t/y LiOH
Clayton Valley	Schlumberger ltd. (Optionee) 100%; Pure energy minerals ltd (optioner)	United States (Nevada)	Brine	100	34	27	6,563 t/y LiOH

Project Name	Owners	Country	Mining Method	Processing plant cost ($M)	Share of initial capital cost (%)	Hydroxide conversion plant cost ($M)	Hydroxide plant capacity
Whabouchi	Investissement Quebec (Venturer) 50%; Livent Corp (Venturer) 50%	Canada	Open pit, underground	730	75	399	21,116 t/y LiOH
Zinnwald	Zinnwald lithium PLC (owner 100%)	EU (Germany)	Underground	238	71	116	6,885 t/y LiOH
South-West Arkansas	Standard lithium Ltd (optionee) 100%; TETRA technology Inc (optioner)	United States	Brine extraction	433	50	91	17,121 t/y LiOH

Source: (S&P Global 2022b)

Figure 7: Growth trend in lithium chemical processing over the last four years



Note: LCE = lithium carbonate equivalent.
Source: (International Energy Agency 2023)

As specified earlier and seen in Figure 7, currently around half of all lithium is mined in Australia, mainly in the mining-friendly jurisdiction of Western Australia. Most of the spodumene concentrate is then shipped to China for processing it into the lithium hydroxide used to make cathodes for batteries (S&P Global 2019). The top three countries – China, Chile and Argentina are responsible for more than 95% of lithium refining. The Australian Bureau of Statistics reports that in every month of 2021, 85% of the total value of Australian lithium concentrate produced was exported to China for processing and usage (Australian Bureau of Statistics 2022). By June 2022, 97% of Australian lithium was exported to China, highlighting the lack of a global alternative to China in the processing industry (Goel et al. 2023).

Given the recent price trends and high geographical concentration in lithium processing, there is a growing interest from miners, merchant refiners and lithium producing countries to capture value by taking strategic positions in the midstream segment. For example, Tees Valley Lithium, or TVL, a U.K.-based refiner is investing in a lithium-sulphate refining facility in Australia. By 2024, Australia may have about 10% of global lithium hydroxide refining capacity, rising to about 20% of global lithium refining by 2027, up from less than 1 percent today (Department of Industry, Science and Resources, Commonwealth of Australia, 2022). Similarly, mining company Albemarle announced plans to invest USD 1.3 billion in a new lithium processing facility in South Carolina, USA in March 2023 (Reuters 2023). Last year, Rock Tech Lithium Inc. announced the completion of a bankable project study for the construction and operation of a proposed battery grade merchant lithium hydroxide monohydrate converter and refinery facility with production capacity of 24,000 tonnes in Guben, Germany. The initial capital cost of the project is estimated to be USD 683 million with a pre-tax IRR of 24% (PR News 2022).

Further, downstream EV makers have often expressed that lithium midstream processing and refining continues to remain one of the biggest bottlenecks for the EV supply chain. As a result, EV makers are increasingly looking to secure lithium supplies directly. In May 2023, Tesla announced its plan to build a new lithium hydroxide refinery on the Texas Gulf Coast, making it the first US EV maker to refine its own lithium and create backward linkages (Bellan 2023). In fact, during its groundbreaking ceremony, Elon Musk urged entrepreneurs to enter the lithium refining business, calling it akin to "minting money" (Jin and Scheyder 2023).

In January 2023, General Motors announced it would invest USD 650 million in Lithium Americas to help the developer progress their Thacker Pass lithium mine in Nevada (General Motors Company 2023). In a significant development, after a pilot that ran for over two years, in partnership with Aquatech, Lithium Americas has achieved over 99.9% purity of Li_2CO_3 from Thacker Pass lithium-bearing clays (Aquatech 2023). Thacker Pass is expected to be one of the largest lithium developments in the world, with the potential to produce over 80,000 metric tons of lithium carbonate per year (Aquatech 2023).

However, data suggests that most of the planned projects are still being developed in incumbent regions, with nearly 49% of planned lithium refining facilities in China, followed by 16% in Argentina and 11% in Australia (International Energy Agency 2023). New investments are being made to build value-added products in the country – either in conversion capacities closer to mines or in consumer countries.

3.7 Key companies involved in the supply chain

The largest lithium-producing companies include Albemarle (USA), which supplies major clients like Tesla and Panasonic; Sociedad Química y Minera de Chile, or SQM (Chile), which serves clients such as LG Energy Solution and SK Innovation; and Tianqi Lithium (China), with major clients including CATL. Ganfeng Lithium (China) supplies Tesla, LG Chem, Samsung, and Volkswagen, while Mineral Resources Ltd (Australia) serves clients like Panasonic and Samsung. Allkem Limited (Argentina) supplies Toyota, and Livent Corporation (USA) works with Tesla and General Motors. Lithium Americas (Canada) is also a supplier to General Motors, while Global Lithium and Lake Resources, both based in Australia, count SK Innovation among their major clients (Goel et al. 2023).

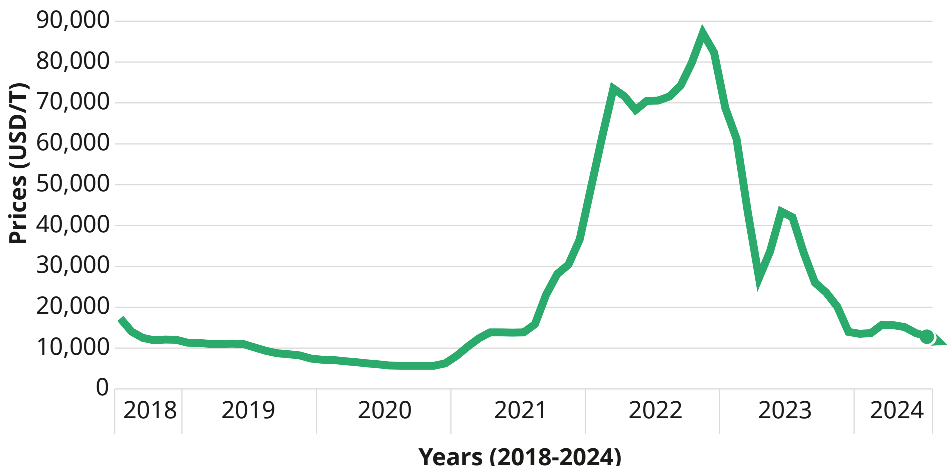
Today, key projects in the upstream production and processing of lithium are often joint ventures between multiple lithium mining and chemical companies. For instance, many Chinese companies have been acquiring lithium mining rights in Latin America and Africa (Goel et al. 2023). Tianqi Lithium owns a 26% share in Greenbushes, Australia, and a 22% stake in SQM's operations in Chile. Ganfeng Lithium holds stakes in projects in Argentina, the US, Mexico, and Australia. CATL and Huayou Cobalt have interests in projects in the Democratic Republic of the Congo, while Sinomine has stakes in lithium projects in Canada and Zimbabwe.

Chinese companies are not the only ones investing in overseas projects. Mineral Resources partnered with Albemarle to build a hydroxide processing facility in Australia; Albemarle holds a 49% stake in Talison Lithium in Australia (Goel et al. 2023). Wesfarmers partnered with SQM to build a hydroxide processing facility in Australia, and Mineral Resources has joint ventures with Ganfeng Lithium and Albemarle. Livent and Allkem have recently announced their merger to create a $10.6 billion lithium producer, making the new company the fifth-largest lithium producer (Attwood and Steel 2023).

In addition to joint ventures, several OEMs are directly investing in lithium projects through offtake agreements or equity participation (Goel et al. 2023). Companies such as BYD, Volkswagen, Mercedes-Benz, Stellantis, General Motors, and Ford are aggressively pursuing vertical integration and offtake agreements to mitigate risks in upstream investments and production:. Notably, GM recently announced a $650 million investment in a US lithium mine to secure offtake agreements. For instance, Stellantis NV, an electric vehicle producer, signed an agreement with Controlled Thermal Resources Ltd for the supply of lithium hydroxide up to 25,000 metric tonnes per year for ten years (Stellantis 2022). Whereas China's electric vehicle manufacturer NIO Inc. announced to pay about USD12 million for acquiring a stake of 12.16% in an Australian lithium mining company 'Greenwing Resources (Liao 2022).

3.8 Markets and Pricing

Figure 8: Global lithium Prices



Source: (Trading Economics, n.d.)

The lithium market's reliance on only 16 projects in three countries exposes it to potential supply disruptions, such as operational challenges or severe weather affecting port operations. These interruptions can drive up prices and hinder the deployment of critical technologies.

The push to decarbonise transportation has led to rising lithium prices over the years. Prices reached unprecedented levels in 2021 and 2022 before easing in 2023. The cost of lithium-ion batteries increased by 10% in 2021 and 2022, marking the first price rise for batteries. Despite this, prices have stabilized, suggesting a high baseline cost for lithium. The price drop in 2023 was particularly noticeable in China, due to the end of electric vehicle subsidies and manufacturers depleting their stockpiles. Lithium prices continued to decline in early 2023 due to reduced lithium purchases and increased domestic demand in China. However, rising electric vehicle and battery sales have helped to recover lithium market prices. Supportive policy frameworks for electric vehicle production and sales in various countries have also contributed to the rebound in lithium prices.

The lithium market is prone to price fluctuations due to market dynamics and political factors, such as China's dominant share of the lithium market and sanctions on Russian lithium suppliers following the invasion of Ukraine. Despite this, the global lithium market is expected to quadruple by 2030, with early investors potentially reaping significant profits.

A lithium shortage is anticipated globally, with Benchmark Minerals Intelligence projecting a 12.5% deficit by 2030 under a base scenario, and the IEA forecasting a 35% supply deficit relative to net-zero requirements, even with current expansion plans..

From 2019 to the start of 2021, the spot prices for spodumene concentrate and battery-grade lithium hydroxide hit their cyclical lows, leaving merchant converters with negligible profit margins when processing spodumene into lithium chemicals. However, the industry experienced a dramatic transformation from late 2021 onwards.

In 2022, the average spot price for spodumene concentrate surged to USD 4,368 per tonne, marking a 550% increase over the previous three-year average. Similarly, the spot price for battery-grade lithium hydroxide skyrocketed to an average of USD 69,370 per tonne in 2022, a 470% increase over the same period. The trend was mirrored in the spot prices for battery-grade lithium carbonate. Estimates indicate that conversion margins in 2022 could have reached as high as USD 13,000-16,000 per tonne of chemicals produced. As of 2023, prices have begun to stabilise due to destocking in Chinese markets and the influx of supply from both established producers and newcomers.

Experts predict that lithium prices will continue to decrease but are unlikely to return to the lows seen in 2019 and 2020. The average spot price for spodumene concentrate is expected to hold steady in 2023 before dropping to an average of USD 2,740 per tonne in 2024 and further to USD 2,149 per tonne in 2025 (Department of Industry, Science and Resources, Commonwealth of Australia, 2023). The decline in lithium hydroxide prices is anticipated to be steeper, with prices forecasted to fall to around USD 46,746 per tonne in 2023, then to approximately USD 35,416 per tonne in 2024, and finally to USD 30,357 per tonne in 2025.

3.9 Agreements and Contracts

While government support aims to boost industry confidence and make project financing more appealing, developers are also proactively securing equity and offtake agreements with original equipment manufacturers (OEMs) and industry end-users in the automotive sector. The tables in Annexure 10 and 11 – Volume 1 provide an overview of recent agreements, investments, and joint ventures. This section provides an overview for all battery minerals, including lithium, nickel and manganese.

Given the increasing volatility of CETM prices, particularly for lithium and nickel, more industry end-users, including automotive OEMs, are securing offtake agreements with mining companies. These agreements are predominantly focused on mineral-rich countries such as Indonesia, Australia, and Canada. Large automotive players, eager to electrify their fleets cost-effectively, are engaging with mining companies early to ensure long-term supply at more stable rates. Most agreements are still in the early stages, with production expected to commence after 2025.

LG Energy Solutions (LGES), alongside other electronic OEMs, has quickly signed such agreements with Canadian miners. In September 2022, LGES secured deals with Snow Lake Resources Ltd., Electra Battery Materials Corporation, and Avalon Advanced Materials Inc. to obtain both lithium and cobalt. Under a binding term sheet with Electra, LGES will receive 7,000 tons of cobalt sulphate annually from 2023 to 2026. Notably, Electra is the only North American supplier capable of refining cobalt sulphate (LGES 2023).

The price points of these agreements vary based on geography, minerals, and the companies involved. Prices often have a floor and ceiling range, are determined by stakeholder formulas, or are pegged to indices like the London Metals Exchange (LME). In the lithium market, surging demand has shortened supply deals, with prices increasingly linked to the spot market. Exchanges in Chicago and Singapore are experimenting with new futures contracts. Companies like Glencore are expanding their market presence through joint ventures and investments in Argentine mining projects (Li, Biesheuvel, and Beaupuy 2023).

Nickel and lithium prices have experienced significant volatility in recent years. Between 2021 and 2022, lithium prices soared due to supply disruptions from COVID-19 and increased demand from government incentives. However, prices began stabilizing in late 2022 and declined in 2023, with ample cathode inventories allowing buyers to negotiate lower prices or delay purchases (G. Williams 2024). Prices falling sharply in 2023 following two years of dramatic increases. According to the IEA (2024), battery materials saw particularly large declines with lithium spot prices plummeting by 75% and cobalt, nickel, and graphite prices dropping by 30-45% (International Energy Agency 2024). The LME is actively creating hedging and trading opportunities for battery metals by introducing futures and contracts to stabilize prices (London Metal Exchange, n.d.).

Long-term supply agreements aim to mitigate price volatility, often basing prices on spot market rates for commodities like lithium hydroxide, lithium carbonate, and spodumene. East Asian and Chinese spot markets serve as benchmarks for lithium prices. As of October 2022, the lithium market was valued at about $30 billion and is expected to keep growing. Increased agreements between OEMs, manufacturers, and miners are expected to lead to greater market concentration, potentially driving prices up by reducing buyer choices and new market entrants.

The nickel market, valued at slightly over $20 billion annually, sees most demand from the stainless-steel industry. Like lithium, nickel is traded on exchanges such as the LME. Prices fell to $20,000 per tonne in early 2023 (Hong et al. 2022). but are expected to average $27,000 per tonne by 2024 due to rising EV market demand(Parker 2023). Indonesia and China are anticipated to be major contributors to global nickel production, impacting price fluctuations. Given its widespread use in steel industries, nickel remains a highly tradable commodity.

3.10 Recycling

The recycling of lithium-ion battery (LiB) cathodes involves various technologies, each suited to different types of cathode chemistries. These technologies include hydrometallurgy, pyro metallurgy, and direct recycling. Here's an overview of these technologies as applied to different LiB cathodes. Each recycling technology offers unique advantages and limitations, making it suitable for various applications depending on the specific cathode chemistry and the intended recovery goals.

Table 6: Recycling technologies for different lithium-ion battery cathodes

S.N.	LiBs Cathode	Recycling Technologies
1	$LiCoO_2$	Hydro metallurgy, Pyro metallurgy, Direct Recycling
2	$LiFePO_4$	Direct Recycling
3	$LiMn_2O_4$	Direct Recycling
4	$LiAlxCoyNi_{1-xy}O_2$	Hydro metallurgy, Pyro metallurgy, Direct Recycling
5	$LiCo_xMn_yNi_{xy}O_2$	Hydro metallurgy, Pyro metallurgy, Direct Recycling

Direct	Pyro metallurgy	Hydro metallurgy
• Disassemble and material separation • Addition of Li source • Calcination • Regenerated active material for a new battery	• Addition of reductant and/or slag-forming agents • Reductive smelting (Hazardous gases) • Recovered Transition Metal Alloy 1. Pyrolysis: Water and Mercury are evaporated, separated and condensed. 2. Reduction: The metallic fraction that	• Inactivation and comminution Separation • Acid Leaching • Precipitation • Recovered Transition Metal and/or Li salts

3.11 Lithium Consumption and Production in India

India's imported lithium compounds in 2021 amounted to USD 24 million for lithium oxide and hydroxide, and USD 9 million for lithium carbonates (UN Comtrade, n.d.). These figures are currently limited due to India's nascent progress in battery cathode manufacturing. However, to achieve the government's target of localising the value chain by promoting domestic cathode and battery cell production, these import numbers are likely to increase in the coming years.

In 2021, India's primary import partners for lithium hydroxide were Russia (44%), Belgium (19%), China (12%), Latvia (10%), and the UAE (8%). For lithium carbonate, the largest trading partners were the US (31%), Belgium (28%), Austria (7%), Singapore (7%), and China (5%) (UN Comtrade, n.d.).

Figure 9 (a): India's import partners for lithium hydroxide in 2021

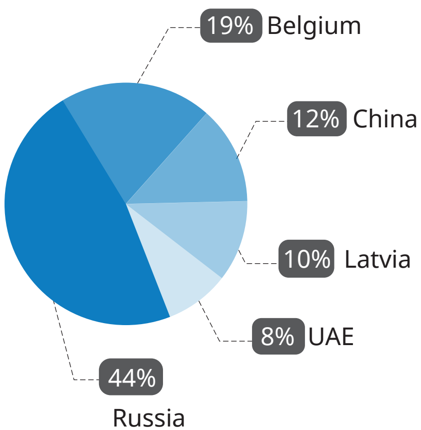
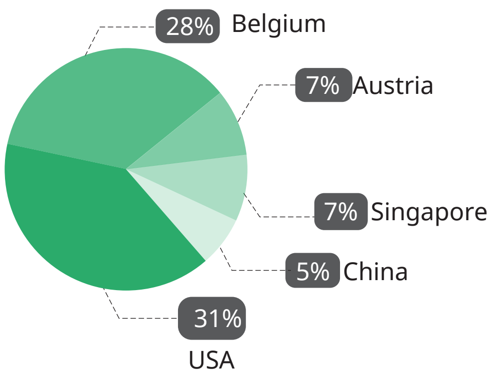


Figure 9 (b): India's import partners for lithium carbonate in 2021



Source: (UN Comtrade, n.d.)

India's recent find of 5.9 million tonnes of lithium reserves in Jammu and Kashmir (J&K) could be significant, since it represents about 6% of the total identified lithium resources in 2023 (USGS 2023). However, international experience shows it takes 16.5 years on average to develop projects from discovery to first production (International Energy Agency 2021). In addition, the J&K resources are currently at an inferred G3 stage, so further exploration will be needed to determine the extent of the reserves that are economically recoverable (Press Information Bureau 2023a).

In the midstream value chain, currently, there is only one lithium refining facility proposed in India. Manikaran Lithium Private Limited signed a Memorandum of Understanding with the state government of Gujarat to develop a lithium refinery to produce battery-grade lithium hydroxide at a proposed cost of INR 2,200 crore (US$296 million) (U. Gupta 2022). It is expected to create around 1,000 direct and indirect jobs. Manikaran had previously partnered with Neometals of Australia for conducting feasibility studies and is now looking to secure its own lithium supply through offtake agreements or equity agreements (Goel et al. 2023). In an interesting development, India's nascent EV makers are also moving further up in battery value chain with Ather Energy announcing its entry into the lithium-ion cell manufacturing space, demonstrating local demand creation by domestic EV manufacturers (Naik 2023).

The Ministry of Mines has setup a Mission Mode Project on Strategic Minerals – Production of Lithium Salts from Ores to carry out R&D work through the CSIR-National Metallurgical Laboratory. The project is expected to run for one year with seed money of INR 12.936 lakh (Indian Bureau of Mines, 2023b). This is significantly lesser than the R&D expenditure made by resource-rich nations. As in the case of China, the government could explore providing direct funding through grants and preferential loans to support R&D as well as pilot plant developments (IEA 2023).

The Indian Government's recent move to exempt custom duties on capital goods and machinery for the production of lithium-ion cells has the potential to stimulate demand for refined and processed lithium products (Varun Singh

2023). This decision underscores the need for the government, at both the state and national levels, to encourage the establishment of lithium refining plants within the country. The government could facilitate this by assisting refining companies in securing land and permits, and by offering incentives to lower their capital costs.

India is well-positioned to develop lithium refineries due to its expertise in chemical processing, robust port and trade infrastructure, anticipated growth in battery demand, lower capital expenditure requirements, and advantageous trade agreements with key partners such as Australia, Chile, and the US. The government is contemplating the inclusion of lithium refining under a Production Linked Incentive scheme for the chemicals sector, having already identified 50 chemicals for potential incentives (Department of and Petrochemicals, 2022; Kundu, 2023).

India has been recognised as an emerging hub for chemicals manufacturing, with its chemical processing sector ranking sixth globally in terms of revenue. The country's chemical manufacturing industry is supported by both state and national governments through initiatives like the Petroleum, Chemicals & Petrochemicals Investment Regions (PCPIRs). These regions, including Andhra Pradesh, Gujarat, Odisha, and Tamil Nadu, are designated zones that are conducive to development and benefit from their extensive coastlines (Goel et al. 2023).

These states are ideal for lithium refining due to their access to government support and ports, which would enable India to import lithium concentrate from Australia and other sources for domestic use or export (Goel et al. 2023). McKinsey reports that infrastructure costs in India are 70% lower than in other chemical processing countries, giving India a competitive edge (McKinsey 2023b). Additionally, India's labour cost competitiveness and the availability of an experienced workforce in the chemical refining sector further enhance its attractiveness for lithium refining.

Domestic lithium refineries would allow India to leverage its partnership and free trade agreement with Australia, particularly for lithium spodumene imports (Goel et al. 2023). However, once lithium is processed in a third country like China, it no longer falls under the free trade agreement. Despite Australia's efforts to develop its own refineries, competition for their lithium is expected to be intense, driven by international automotive companies seeking to comply with the Inflation Reduction Act. The Australia-India Strategic Research Fund offers grants to enhance collaboration on critical minerals processing, recycling, and tailings reclamation, which could provide India with essential raw materials and technologies.

The development of lithium refineries in India is not only crucial for meeting current import needs but also for preparing the country to exploit its domestic lithium reserves. By investing in refining capabilities now, India can build a strong foundation for processing domestically sourced lithium in the future.

4

MANGANESE

4 MANGANESE

4.1 Natural Occurrence

Manganese (Mn) is the twelfth most abundant element, known for being a hard, brittle, silvery metal. It commonly occurs in minerals with iron, silicon, and laterites. Manganese is crucial in battery production, especially in lithium-ion batteries where manganese dioxide enhances energy density and longevity. Manganese is found in ores like pyrolusite, psilomelane, and rhodochrosite, and exists in various oxidation states.

4.2 Resources

Global manganese resources are estimated to be around 17 billion metric tonnes, with South Africa holding approximately 70% of these resources (USGS 2023). In India, manganese resources were estimated to be 503.62 million tonnes in 2020 (Indian Bureau of Mines 2023a).

4.3 Production and Reserves

In 2022, the global production of manganese was 20 million metric tonnes based on manganese content, and the estimated reserves were 1.7 billion tonnes. Figure 10 illustrates the top producers of manganese and their reserves in 2022 (USGS 2023). In India, the production of manganese ore was approximately 2.68 million metric tonnes during the 2020-21 period. The reserves of manganese ore in India in 2020 were estimated to be 75.04 million metric tonnes (Indian Bureau of Mines 2023a).

Table 7 Manganese Production and Reserves

Country	Mine Production		Reserves
	2021	2022	
United States of America	-	-	-
Australia	3,260,000	3,300,000	270,000,000
Brazil	542,000	400,000	270,000,000
Burma	206,000	200,000	Not available
China	991,000	990,000	280,000,000
Cote d'Ivoire	362,000	360,000	Not available
Gabon	4,340,000	4,600,000	61,000,000
Georgia	224,000	220,000	Not available
Ghana	940,000	940,000	13,000,000
India	453,000	480,000	34,000,000
Kazakhstan, conc.	90,000	110,000	5,000,000
Malaysia	356,000	360,000	Not available
Mexico	226,000	230,000	5,000,000
South Africa	7,200,000	7,200,000	640,000,000
Ukraine, conc.	600,000	400,000	140,000,000
Vietnam	146,000	150,000	Not available
Other Countries	150,000	150,000	Small
Total	20,100,000	20,000,000	1,700,000,000

Source: (USGS 2023). Data in metric tonnes.

Figure 10(a): Global manganese mine production (Mn content) in 2022

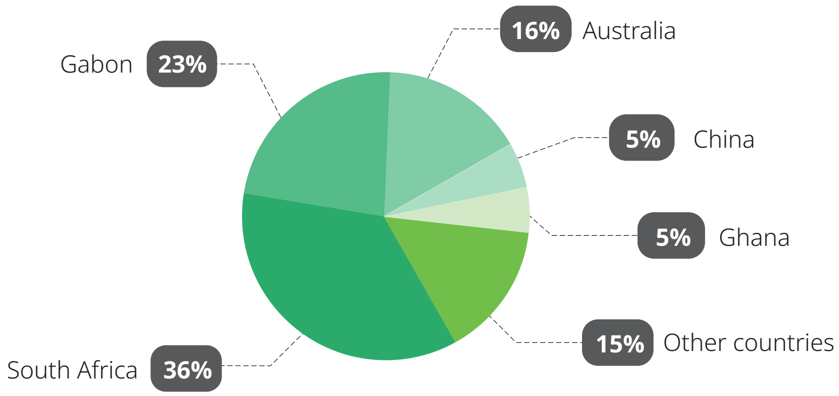
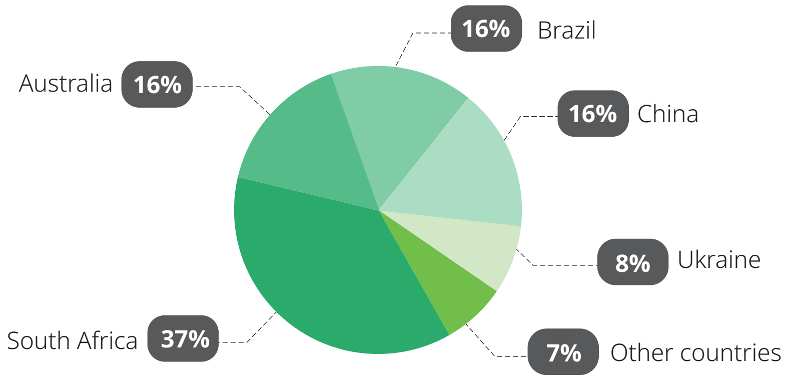


Figure 10(b): Global manganese reserves in 2022



Source: (USGS 2023).

Figure 11(a): Production of Manganese Ore in India, 2020-21

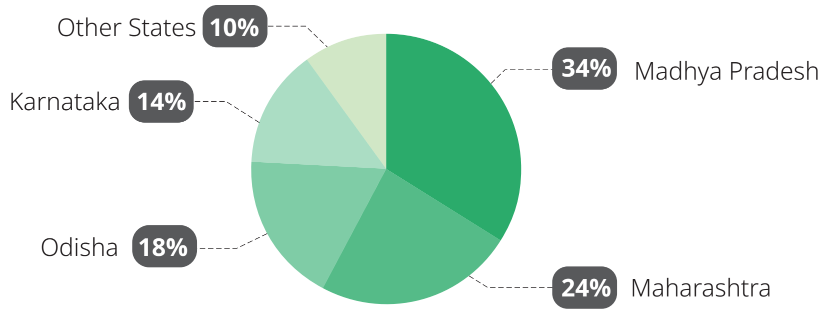
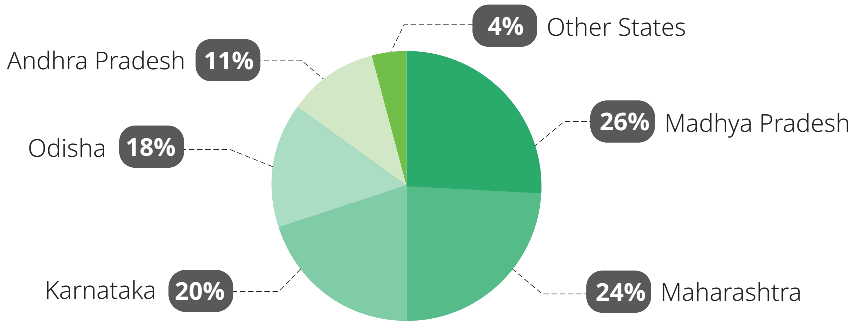


Figure 11(b): Reserves of Manganese Ore in India, 2020



Source: (Indian Bureau of Mines 2023a)

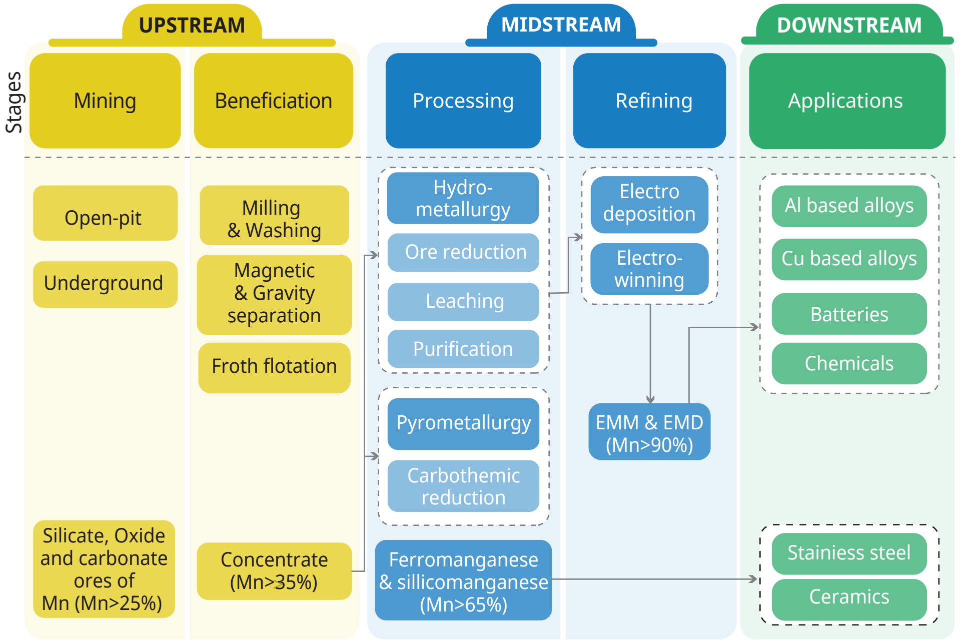
4.4 Processing

The processing route for manganese ore depends on the ore's grade and the impurities present. Manganese ores are mainly classified as oxides, silicates, and carbonates. Examples include pyrolusite (MnO_2), braunite ($3Mn_2O_3$, $MnSiO_3$), and rhodochrosite ($MnCO_3$), respectively (Indian Bureau of Mines 2023a)

High-Grade Ores: Ores with over 46% manganese are either sold directly or sent to the ferromanganese or silicomanganese alloy industry.

Low and Medium-Grade Ores: These ores undergo beneficiation through gravity separation, magnetic separation, and froth flotation methods before being used in ferroalloy production. The production of ferromanganese and silicomanganese involves carbothermic reduction in a blast furnace or submerged electric arc furnace at temperatures above 1500°C. For every tonne of ferromanganese produced, approximately 0.5 tonnes of reductant, 2.6 tonnes of manganese ore, and 3 MWh of power are required (Veerendra Singh, Chakraborty, and Tripathy 2020).

Figure 12: A simplistic representation of the value chain stages of Manganese



Source: Authors' representation based on (Veerendra Singh, Chakraborty, and Tripathy 2020; Bam, Zyl, and Steenkamp 2016; Biswal et al. 2015

In the future, deep-sea polymetallic nodules could become a significant source of manganese. The processing of these nodules, currently in the research phase, may involve a combination of pyrometallurgical and hydrometallurgical methods (Ju et al. 2023).

4.5 Extent of value Addition in Mid-Stream

Significant value can be gained from manganese mining and processing. For example, ferromanganese, which is a combination of manganese and iron, can command prices up to three times higher than manganese ore. Similarly, manganese steel, an alloy of manganese and carbon known for its strength, can be sold for prices up to ten times greater than manganese ore.

4.6 Manufacturing and Use

Around 90-95% of global manganese production is used in the iron and steel industry to improve strength, hardness, and toughness as a deoxidiser and desulfuriser. It is also used in chemical processes, pigments, and ceramics.

Electrolytic manganese dioxide (EMD), which contains a minimum of 90% MnO2 and minimal impurities, is essential for dry cell batteries. China is responsible for 90% of global Mn refining (IRENA 2023). In India, Manganese Ore India Limited (MOIL) has established a plant in Bhandara district, Maharashtra, with a capacity of 1,000 tonnes per annum (tpa). This plant produced 1,070 tonnes and 925 tonnes of EMD in 2020-21 and 2019-20, respectively (Indian Bureau of Mines 2023a).

4.7 Investments in Mining and Processing

Manganese is witnessing a surge in global demand expected to persist in the upcoming years. This heightened demand is propelled by the increasing necessity for applications. Recent years have seen a notable uptick in investments directed towards manganese mining and production. In 2021 alone, global investments in manganese projects soared to $1.2 billion, marking a substantial increase from $800 million in 2020. Several factors contribute to this surge in investment, including the escalating demand for manganese, its growing scarcity, and the imperative to secure long-term supplies.

While South Africa remains the focal point of manganese investment as the largest global producer, there is a growing interest in manganese projects in other nations such as Australia, China, and India. The upswing in manganese investment presents a favourable outlook for the global economy, ensuring an adequate supply of manganese to satisfy escalating demands. Nevertheless, it's worth noting that the manganese market still grapples with volatility, raising the possibility of sharp price hikes in the future.

4.8 Key companies involved in the supply chain

Top companies involved in the production of Manganese are Assmang (South Africa), BHP Billiton (Australia), South 32 Limited (Australia), Eramet (France), Vale (Brazil) and Manganese Ore India Limited (India).

In India, Manganese Ore India Limited (MOIL) is a major player, producing 45% of India's manganese. MOIL operates a beneficiation plant with an annual capacity of 400,000 tonnes at the Dongri Buzurg mine in Maharashtra and a plant with a capacity of 500,000 tonnes at the Balaghat mines in Madhya Pradesh. MOIL also manufactures electrolytic manganese dioxide (EMD) at a plant in Maharashtra with an annual capacity of 1,500 metric tonnes and runs a ferromanganese plant in Madhya Pradesh with an annual capacity of 12,000 metric tonnes.

4.9 Pricing and Markets

The manganese market has experienced uncertainties and depressed prices from 2018 to early 2020 due to several factors, including increased production in Africa, expanded silicomanganese capacities in China, and higher manganese ore shipments from South Africa, the largest global producer followed by China. The COVID-19 pandemic further impacted manganese prices, with China's lockdown measures disrupting logistics and slowing the flow of manganese for steelmaking. However, prices surged after China's market reopened and steel production resumed. In late 2020, manganese prices dropped again following the lifting of South Africa's lockdown and the consequent increase in shipments. Besides its use in steelmaking, manganese saw significant demand from battery producers, as manganese sulphate is a key component in lithium-ion battery chemistries. The complexities of producing battery-grade manganese, which only a few countries can achieve, have added to the price volatility and highlighted supply chain vulnerabilities

4.10 Agreements and Contracts

Refer Agreements and Contracts in section 3.9 of Volume II.

4.11 Recycling

Although recycling manganese is feasible, it is not as widespread as with other metals. Recycling methods include pyro metallurgical processes, where manganese-containing scrap is melted and refined, and hydrometallurgical techniques, involving the dissolution of manganese from scrap using acids. Pyro metallurgical methods entail heating the ore with carbon to yield manganese dioxide, which can then be further processed to obtain pure manganese metal. Electrolytic processes are utilised for refining manganese metal, while leaching involves treating the ore with acid to dissolve manganese compounds.

With the growing use of manganese in lithium-ion batteries, recycling spent batteries has become an essential source of high-purity manganese. Battery recycling processes extract manganese dioxide, which can be refined and reused in new batteries. Hydrometallurgical processes are particularly useful for recovering manganese from battery scrap, where high-purity manganese is required. This method often involves steps such as leaching, solvent extraction, and precipitation to produce refined manganese compounds. Recycling manganese is generally more energy-efficient than extracting and processing new ore, leading to lower energy consumption and reduced carbon footprint. The recycling of manganese, especially from complex products like batteries, requires advanced technologies and processes that can be technically challenging and expensive to implement. The high purity required for certain applications, such as battery-grade manganese, can complicate the recycling process and increase costs.

4.12 Manganese Consumption and Production in India

India is the world's sixth-largest producer of manganese. However, a considerable portion of the manganese ore is exported in its raw form, leading to India not fully capitalising on its manganese resources.

India has strong reasons to establish a localised manganese value chain. This approach would promote job creation, stimulate economic growth, and lessen the nation's dependence on imported manganese products. However, there are obstacles to address, including the necessity for investments in infrastructure like smelters and refineries, the requirement for skilled labour, and adherence to environmental regulations.

Despite these obstacles, India possesses the capability to emerge as a significant contender in the global manganese market. Through localising the manganese value chain, India can fully harness the value inherent in its manganese resources and lay the foundation for a sustainable and prosperous future for its populace. Beyond the economic advantages, this localisation would yield numerous social and environmental benefits. For instance, it would generate employment opportunities in rural regions, where many manganese mines are situated. Moreover, it would curtail the necessity to transport large quantities of manganese ore, thereby contributing to a reduction in air pollution.

Presently, MOIL operates both underground and opencast mines in the Nagpur and Bhandara districts of Maharashtra, as well as the Balaghat district of Madhya Pradesh (MOIL Limited, n.d.). These mines have a history spanning about a century. The Balaghat Mine holds the distinction of being the company's largest mine, with a mining depth that has now reached approximately 435 meters below the surface. Another mine, Dongri Buzurg Mine, located in Maharashtra's Bhandara district, focuses on opencast extraction (MOIL Limited, n.d.). This mine contributes manganese dioxide ore, used in the dry battery industry. The manganous oxide form of this ore serves as a micro-nutrient for cattle feed and fertilizers. MOIL addresses nearly 46 per cent of India's total requirement for manganese dioxide ore (MOIL Limited, n.d.). The current annual production stands at around 1.3 million tonnes, a figure poised for growth in the upcoming years. MOIL's operations encompass the production and sale of diverse manganese ore grades. These include high-grade ores for ferromanganese production, medium-grade ore for silicomanganese production, blast furnace grade ore essential for hot metal production, as well as dioxide tailored for dry battery cells and chemical industries (MOIL Limited, n.d.).

By 2030, the global mining industry will require an additional 300,000 to 600,000 skilled professionals, a demand that could be complicated by the declining number of mining engineering graduates and the current job scarcity. India's growing expertise in manganese mining and processing could help address this labour shortage. Moreover, localising the manganese value chain in India would create jobs, drive economic growth, and decrease import dependency.

5

NEODYMIUM

5 NEODYMIUM

5.1 Natural Occurrence

Figure 13: Light and heavy rare earth elements

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
Lanthanides	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Actinides	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Source: Author's representation based on (Indian Bureau of Mines 2023b)

Rare Earth Elements (REEs), comprise 17 elements including neodymium, scandium, and yttrium. These elements naturally occur together and are classified into two groups, Light Rare Earth Elements (LREEs) and Heavy Rare Earth Elements (HREEs), based on atomic weight. LREEs have lower atomic numbers and are more abundant in nature, whereas HREEs have higher atomic numbers and are less common. Although yttrium is not part of the lanthanide series, it is included with the HREEs due to its similar chemical and physical properties. Figure 13 illustrates the atomic symbols and numbers for both LREEs and HREEs (USGS 2023; Goodenough, Wall, and Merriman 2018). neodymium is mainly sourced from the minerals monazite and bastnaesite. neodymium exists in multiple isotopes (142Nd, 143Nd, 144Nd, 145Nd, 146Nd, 148Nd, 150Nd) and has an oxidation state of +3. It has a high relative supply risk of 9.5 and a recycling rate of less than 10%.

5.2 Resources

Global resources of rare earth oxides (REOs) are estimated to be 20.6 billion metric tonnes (USGS 2023). However, mineable deposits are less common compared to other elements.

5.3 Production and Reserves

In 2022, global production of rare earth elements (REEs) was approximately 300 thousand metric tonnes of rare earth oxide (REO) equivalent. Figure 14 illustrates the top producers and reserves of REO in 2022. The estimated world reserves of REEs in 2022 were around 130 million metric tonnes of REO equivalent (USGS 2023).

Table 8 REE Production and Reserves

Country	Mine Production		Reserves
	2021	2022	
United States of America	42,000	43,000	2,300,000
Australia	24,000 (est.)	18,000	4,200,000
Brazil	500 (est.)	80	21,000,000
Burma	35,000 (est.)	12,000	Not available
Burundi	200 (est.)	-	Not available
Canada	-	-	830,000
China	168,000	210,000	44,000,000
Greenland	-	-	1,500,000
India	2,900 (est.)	2,900	6,900,000
Madagascar	6,800 (est.)	960	Not available
Russia	2,600 (est.)	2,600	21,000,000
South Africa	-	-	790,000
Tanzania	-	-	890,000
Thailand	8,200 (est.)	7,100	Not available
Vietnam	400	4,300	22,000,000
Other Countries	60	80	280,000
Total	290,000	300,000	130,000,000

Source: (USGS 2023).
Data in metric tons.

Figure 14(a): Mine production of Rare Earths, 2022

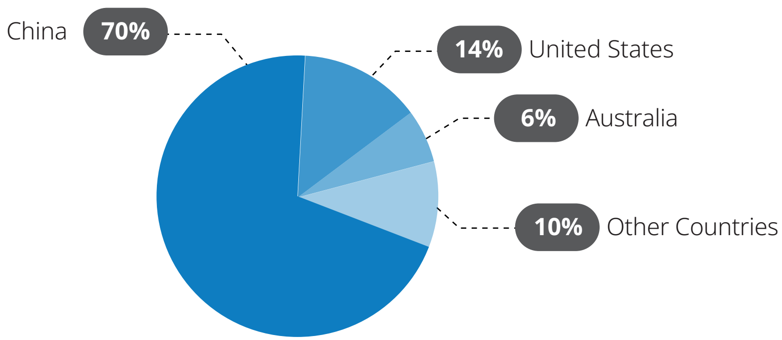
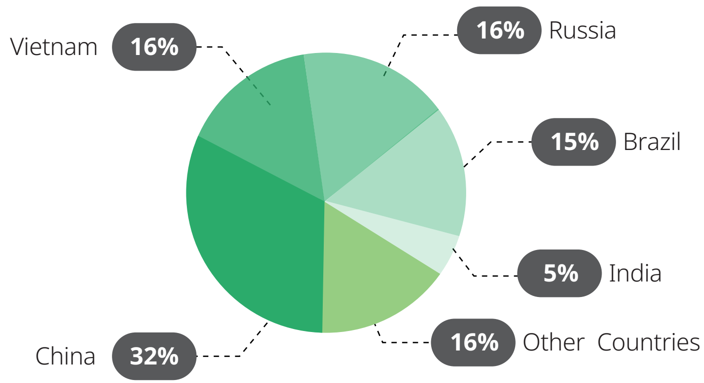


Figure 14(b): Mine production of Rare Earths in 2022



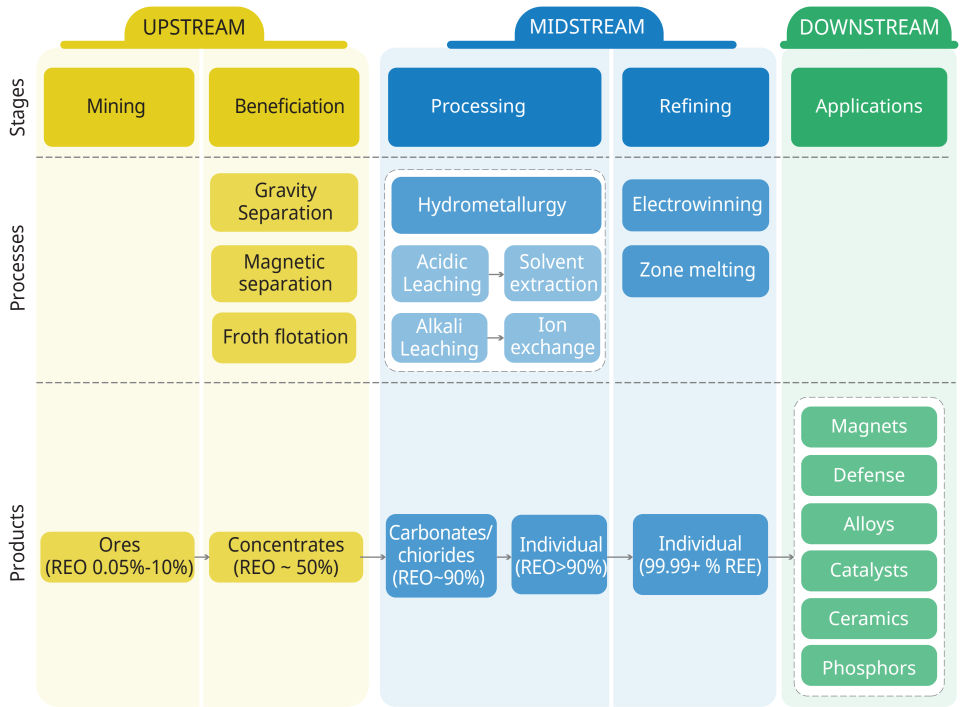
Source: (USGS 2023).

5.4 Processing

Commercially important REE minerals include bastnaesite (a carbonate mineral), monazite and xenotime (both phosphate minerals), and ion-adsorption clays. Significant REE deposits are located in Bayan Obo (China), Mountain Pass (USA), Mount Weld (Australia), and ion-adsorption deposits in Southern China (Cheng et al. 2024).

The primary steps in processing REE ore involve mining, beneficiation, chemical treatment, separation, reduction, and refining, as illustrated in Figure 15.

Figure 15: A simplistic representation of the value chain stages of Rare Earth Elements



Source: Author's representation based on (Cheng et al. 2024; Navarro and Zhao 2014)

India has the capacity to extract metals from its rare earth deposits, particularly light rare earths, with Neodymium and Praseodymium being purified to 99.9% levels. The Indian Rare Earths Limited (IREL) handles the processing of monazite ores and operates several plants, including the Rare Earth Division in Aluva, Kerala, the Odisha Sand Complex (OSCOM), and the Manavalakurichi unit in Tamil Nadu (IREL, n.d.). Despite having the fifth-largest rare earth reserves globally, India's REE production remains modest, partly due to IREL's monopoly. Allowing private sector participation could enhance local production capabilities (Kanisetti, Pareek, and Ramachandran, n.d.).

IREL plans to increase its REE mineral processing capacity from 11,000 to 20,000 tonnes per year. Additionally, IREL is establishing a new Rare Earth Permanent Magnet (REPM) plant in Visakhapatnam under the Make in India initiative (IREL, n.d.). Recently, the Geological Survey of India (GSI) discovered a carbonatite with syenite containing an REE deposit in Chamarajanagar district, Karnataka. After G2 stage exploration, the estimated resource is 4.19 million tonnes with an average grade of 0.5% total rare earth oxide (TREO) content.

5.5 Manufacturing and Use

REEs are essential in manufacturing components for Low Carbon Technologies (LCTs), such as electrolysers, batteries, and military equipment. They also play critical roles in renewable energy, defence, aerospace, electronics, and electrical equipment due to their unique properties. Neodymium, in particular, is vital for the global clean energy transition, especially in electric vehicles and wind turbines, thanks to its superior magnetic properties that enable the conversion of electrical energy to mechanical energy in electric motors.

Neodymium is primarily used in an alloy with iron and boron to create powerful permanent magnets. These magnets have revolutionised many electronic devices, such as mobile phones, microphones, loudspeakers, and electronic musical instruments, enabling their miniaturisation since Neodymium's discovery in 1983. Additionally, these magnets are used in wind turbines and car windscreen wipers.

5.6 Supply Challenges and Growth Prospects for Leading Producers

The primary challenge lies in scaling up the mining and processing operations of REEs across the entire value chain to meet the growing demand, despite ample known rare earth resources available to satisfy the requirements of the energy transition. Moreover, the metallurgy involved in rare earths, encompassing separation, metal production, casting, and magnet production, is highly complex, posing a technological barrier for new entrants into the market.

To address supply concerns and reduce dependency on Nd-Fe-B, which is based on REEs and used in EV motors and wind turbines, alternative solutions like rare earth-free permanent magnets are being explored. Researchers such as Saho and Ren advocate for iron-based permanent magnets due to their abundance and magnetic performance, while studies by Mohapatra and Liu suggest rare earth-free nanostructured permanent magnetic materials as next-generation alternatives (Mohapatra and Liu 2018). In India, scientists at the International Advanced Research Centre for Powder Metallurgy & New Materials (ARCI) have successfully developed heavy REE-free improved permanent magnets (Press Information Bureau 2022).

5.7 Investments in Mining and Processing

The demand for REEs is experiencing rapid growth, yet their supply remains constrained due to the geographical concentration of production. This situation has raised concerns regarding REE supply security, prompting various countries to invest in REE mining and production development. Among the REEs, neodymium holds particular significance as it is utilized in the production of permanent magnets crucial for diverse applications like electric motors and generators. Anticipated growth in neodymium demand in the coming years aligns with the global transition towards clean energy. Recent years have witnessed a notable uptick in investments directed towards neodymium mining and production. In 2021, global investment in neodymium projects surged to $2 billion, up from $1 billion in 2020. This upsurge in investment is propelled by factors such as increasing demand, scarcity of the metal, and the imperative to secure long-term supplies. Notably, the total project cost for rare earth mining and processing stands at $223.96 ($234/t ore) million per annum for a project in South Africa, with processing accounting for approximately 68 percent of this cost. However, costs vary geographically, with lower costs observed in countries like the US (Baskaran 2022).

While the majority of neodymium investment is centred in China, the world's largest producer, there is growing interest in neodymium projects in other countries like Australia, Canada, and the United States (Indonesia Business Post 2023). This surge in neodymium investment bodes well for the global economy, ensuring adequate supply to meet escalating demand. Nonetheless, the neodymium market remains relatively volatile, posing a risk of sharp price increases in the future.

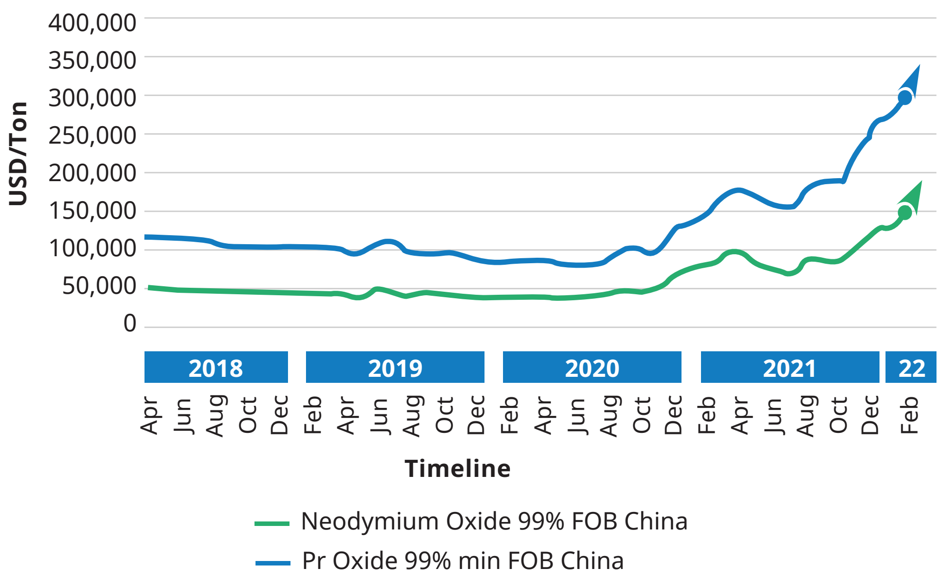
Beyond investment in neodymium mining and production, there is also a growing interest in developing neodymium substitutes. These substitutes could mitigate reliance on neodymium in certain applications and contribute to stabilising the neodymium market. The increased investment in neodymium underscores the industry's proactive approach towards addressing supply challenges, indicating a commitment to finding sustainable solutions for the metal's future.

5.8 Key Players involved in the Supply Chain

The top 10 companies in the world involved in the production of rare earths are China Northern Rare Earth High-Tech Co., Ltd (China), Iluka Resources (Australia), Lynas Rare Earths (Australia), MP Materials (USA), Arafura Resources (Australia), Aclara Resources (Chile) and Rare Element Resources Ltd (USA) (Yahoo Finance 2023).

5.9 Pricing and Market

Figure 16: REEs price variability



Source: (S&P Global, 2022)

Fluctuations in the prices of REEs, notably neodymium and praseodymium oxide, can profoundly impact the demand for technologies reliant on these elements and influence deployment schedules. The depicted figure illustrates the dynamic nature of rare earth prices, with discernible shifts, particularly evident from 2020 onwards. The prevailing upward trajectory in prices underscores potential ramifications for sourcing, processing, and utilisation of these minerals, underscoring the significance of vigilance and effective management of REE markets. India's evolving focus on e-mobility and energy transition further accentuates the need for a reliable REE supply. With heavy import dependence, fostering domestic production and utilisation emerges as pivotal for ensuring REE mineral security.

Despite its rising demand for clean energy systems, neodymium prices remain unpredictable due to supply chain issues, primarily from leading producers like China and the US. The geopolitical risks associated with neodymium trade significantly impact its price stability. Since China is the largest producer and exporter of rare earth elements, any changes in its policies, production levels, or export restrictions can profoundly influence neodymium prices. For example, in 2010, China sharply reduced rare earth exports and halted shipments to Japan to pressure for the release of a detained Chinese fishing trawler captain, causing significant price fluctuations. Consequently, businesses and industries reliant on neodymium often adopt strategies to manage price volatility, such as diversifying suppliers, securing long-term supply agreements, and employing forward contracts to ensure stable supply and predictable pricing. The neodymium market's volatility underscores the importance of supply chain resilience, risk management, and diversification strategies for industries dependent on this critical raw material.

5.10 Agreements and Contracts

a) Manufacturers of Light Commercial Trucks, such as Stellantis and NioCorp, are increasingly engaging in offtake agreements to secure the supply of REEs. Stellantis, based in the Netherlands, is the parent company of 14 automotive brands, including Fiat, Jeep, Opel, and Maserati, some of which are leading global automobile manufacturers. As part of its goal to achieve carbon neutrality by 2038, Stellantis has introduced an aggressive electrification roadmap, investing €30 billion by 2025 to boost its EV sales (Stellantis, n.d.). To support this plan, Stellantis aims to secure minerals like Neodymium-Praseodymium oxide (NdPr) from NioCorp, a US-based mining and processing company focused on critical minerals. Their recent 10-year offtake agreement ensures a stable supply of NdPr and other essential raw materials (Stellantis 2023).

b) Similarly, agreements like the one between Arafura Rare Earths Limited and Siemens Gamesa Renewable Energy enhance global access to REEs

(Mulholland 2023). Arafura, an REE development company, produces NdPr oxide at its Nolan Project in Northern Australia (Arafura, n.d.). Siemens Gamesa, a leading German manufacturer of onshore and offshore wind power technology, has entered a five-year offtake agreement with Arafura, extendable by two years (Siemens Gamesa, n.d.). Under this contract, the supply of NdPr will start at 200 tonnes per annum (tpa) in 2026, increase to 360 tpa the following year, and reach 400 tpa from the third year onward. The agreement also specifies the grade of the mineral and other conditions to be met before the contract commences.

c) Leading mining jurisdictions such as Canada currently do not have commercial production of REEs (Government of Canada, n.d.). Original Equipment Manufacturers (OEMs) in Canada, like Neo Performance Materials, are entering offtake agreements to ensure resilient access to REEs. Neo Performance Materials, a Canadian OEM, engages in large-scale production of permanent magnets essential for various LCTs (Neo, n.d.). Neo has signed an offtake agreement with Hastings Technology Metals to supply various Mixed Rare Earth Carbonates (MREC) from the Yangibana Rare Earth Project in Western Australia (Neo 2023). The supply of REEs would be from the Yangibana Rare Earth Project in Western Australia, which contains significant quantities of neodymium and praseodymium resources (Hastings, n.d.). During the ten-year agreement, the supply will be 25,000 tpa during Stage 1 (from 2025) and 10,000 tpa during Stage 2 (from 2028), accounting for 70% of production at the Yangibana project

d) Chinese rare earth processing companies are actively pursuing offtake agreements with leading global REE producers, as seen in the agreement between Shenghe Resources Holding Co. Ltd. and Peak Rare Earths (Reuters, n.d.). These agreements strengthen China's position in the REE supply chain, posing challenges to efforts aimed at reducing dependence on China. Shenghe Resources, a Chinese mining, smelting, and processing company, entered a binding offtake agreement in August 2023 with Peak Rare Earths, headquartered in Australia, for the supply of REEs from Peak's Ngualla Rare Earth Project in Tanzania (Peak Rare Earths 2023). This project holds one of the world's largest and highest-grade NdPr deposits (NS Energy 2023; Peak Rare Earths, n.d.). The agreement stipulates that 100% of the rare earth concentrates and 50% of MREC will be supplied to Shenghe over an initial period of seven years, with Shenghe obligated to pay and take delivery.

e) In 2022, VHM Limited, an Australian REE mining company, signed a similar supply chain agreement with Shenghe. Under this agreement, VHM Limited will sell 60% of its mined minerals from its Victorian mines to Shenghe (Ker 2022).

5.11 Recycling

It is increasingly important to recycle neodymium due to its scarcity and demand. The recycling process is complex and requires advanced technology to efficiently separate and purify neodymium. The cost-effectiveness of recycling can be influenced by market prices for neodymium and the availability of recyclable material. The recycling of neodymium is rare and is usually accomplished through pyro metallurgical recovery, hydro metallurgical processing, and direct recycling. Both pyro metallurgical and hydrometallurgical processes can have significant environmental impacts if not managed properly, including the release of hazardous substances.

5.12 REE Consumption and Production in India

Presently, India heavily relies on China for the majority of its rare earth resources, but vulnerabilities in this dependence were exposed during the 2020 border standoff (Seah and Joshi 2021). To secure its strategic interests, India must explore alternative sources. Despite possessing the world's fifth-largest resources, India is yet to achieve self-sufficiency (Press Information Bureau 2023b; Afonso 2023). The mining and extraction processes for rare earths are capital-intensive, energy-consuming, and produce toxic by-products. Furthermore, the country's rare earth ecosystem is primarily controlled by the government-run Indian Rare Earths Limited (IREL), leading to an underdeveloped midstream and downstream industry, and continued dependence on imports of rare earth magnets (IREL India Limited, n.d.; Press Information Bureau 2023b).

In India, the value chain of REE is yet to be fully developed. The country lacks direct programs for developing the REE value chain, although it has launched initiatives to boost REE demand significantly. With plans to have 30 percent of its automobiles powered by electric energy by 2030, India's investment in the Faster Adoption and Manufacturing of Electric Vehicles (FAME II) initiative is expected to drive demand for permanent magnets and related products, which are crucial drivers of REE demand (Press Information Bureau 2023d).

However, the technology required to convert rare earth oxides into metals or alloys is proprietary and held closely by a few countries (M. Gupta 2022). The lack of local technology expertise and the absence of commercial-scale proven technology transfer led to most of midstream and downstream value-added product imports in India. To elevate India's position in the global REE value chain, substantial investments, technological transfers, and information support are necessary to establish processing units in the country (India Briefing 2022).

6

NICKEL

6 NICKEL

6.1 Natural Occurrence

Most of Earth's nickel originated from meteorites, including a significant impact near Ontario, Canada, which now contributes 15% of global production. Nickel is naturally abundant, primarily recovered from iron/nickel sulphide minerals like pentlandite and garnierite.

The most commonly found nickel sulphide mineral is pentlandite, which is primarily extracted from iron and magnesium igneous rocks located in Russia, South Africa, Canada, and Australia. Nickel laterite ore, making up a significant portion of global resources, contains iron and other contaminants such as copper that must be separated (McKinsey 2020). There are two grades of processed nickel: class 1 and class 2. Class 1 nickel, which is high-purity nickel, is essential for producing nickel cathodes used in batteries, particularly in electric vehicles. In contrast, Class 2 nickel, which has a higher iron content, is predominantly utilised in stainless steel production due to its lower cost and different properties.

Nickel exhibits oxidation states of 3, 2, and 0, and has isotopes including 58Ni, 60Ni, 61Ni, 62Ni, and 64Ni. It has a relative supply risk rating of 6.2. Most mined nickel comes from two main ore types: laterites (60%), used for Class II products in steel production, and magmatic sulphide deposits (40%), which provide feedstock for Class I nickel used in battery cathodes.

6.2 Resources

By 2022, land-based resources with a nickel content of 1% or higher were estimated to total at least 300 million tonnes of nickel, with laterites accounting for 60% and sulphide deposits for 40% (USGS 2023). Australia, Indonesia, South Africa, Russia, and Canada collectively hold over 50% of global nickel resources. Despite significant growth in nickel mining over the past three decades, known reserves and resources have continued to increase steadily. Additionally, there is substantial potential for nickel deposits in deep-sea manganese nodules, which contain various metals, including nickel. Recent estimates indicate that these nodules may harbour more than 300 million tonnes of nickel (Nickel Institute, n.d.). However, the declining discovery of new sulphide deposits in conventional mining areas has prompted exploration efforts to expand into more challenging regions such as east-central Africa and the subarctic (Calvo et al. 2016).

6.3 Production & Reserves

Currently, nickel-containing ores are extracted in more than 25 countries worldwide. However, Indonesia and the Philippines stand out, accounting for 45% of global nickel output. Their dominance in nickel production is expected to grow in the coming years. The majority of mined nickel comes from two main types of ore deposits: laterites, used for Class II products in steel production, and magmatic sulphide deposits, which provide the feedstock for the higher-grade Class I nickel, commonly used in cathode production for batteries. Countries like Canada, Russia, and South Africa primarily mine sulphide-type deposits, while Indonesia, the Philippines, Brazil, Cuba, and New Caledonia focus more on laterites. Due to their geological formation, equatorial regions are the primary locations for laterite-type deposits and mines. In Australia, both laterite and sulphide mining operations are carried out. Collectively, these nine countries hold about 75% of global nickel reserves (USGS 2023).

Table 9 Nickel Production and Reserves

Country	Mine Production		Reserves
	2021	2022	
Australia	151,000	160,000	21,000,000
Indonesia	1,040,000	1,600,000	21,000,000
China	109,000	110,000	2,100,000
Russia	205,000	220,000	7,500,000
Brazil	76,000	83,000	16,000,000
Canada	134,000	130,000	2,200,000
United States of America	18,400	18,000	370,000
New Caledonia	186,000	190,000	7,100,000
Philippines	387,000	330,000	4,800,000
Other countries	429,000	440,000	20,000,000
Total	2,730,000	3,300,000	100,000,000

Source: (USGS 2023).
Data in metric tonnes.

6.4 Processing

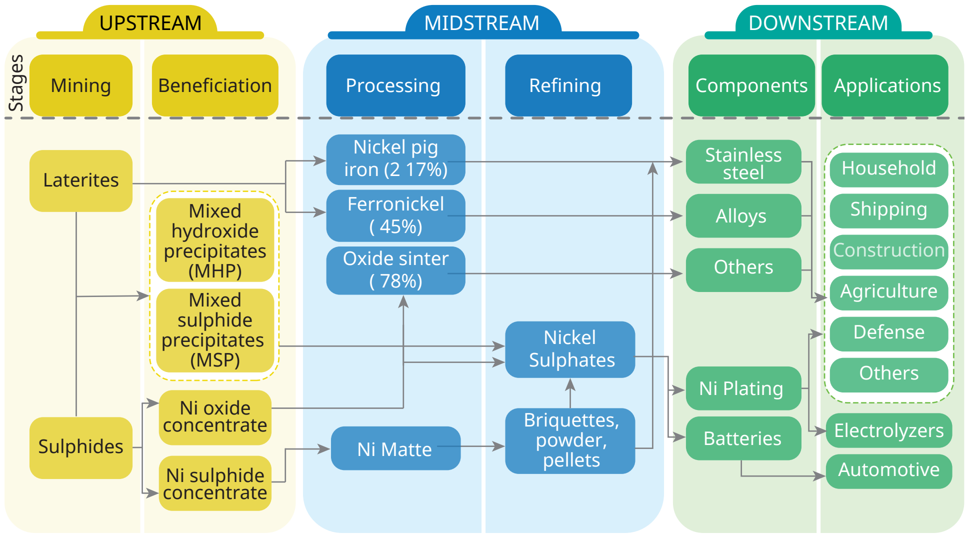
Over the past decade, global nickel production has surged by over 65%. Approximately 46% of the finished nickel products worldwide are classified as Class I nickel, with the majority being Class II nickel (Azevedo, Goffaux, and Hoffman 2020). China has played a dominant role in nickel refining, accounting for 68% of global nickel refining. However, this dynamic shifted dramatically when Indonesia imposed an export ban on nickel ore in 2020. This ban disrupted the flow of raw nickel to China and prompted Indonesia to rapidly develop its own downstream processing capacity, largely with support from foreign, particularly Chinese, investors. As a result, Indonesia now contributes over 38% of the global supply of refined nickel. Between 2021 and 2025, Indonesia is projected to drive approximately half of the global growth in nickel production. The success of Indonesia's High-Pressure Acid Leaching (HPAL) projects, albeit with environmental concerns, is crucial for the future global supply of nickel for batteries, at least in the short term.

6.5 Extent of value addition in midstream stages

Globally, nickel reserves are found in the form of laterites (60%) and sulphide deposits (40%). Nickel ores are mined in about 33 countries and are smelted or refined in about 30 countries. However, three countries – namely Indonesia, China and Japan are responsible for more than 50% of nickel refining (USGS 2023). While in the case of China, interest in nickel refining is mainly driven due to rising demand for stainless steel and non-stainless applications such as LCTs (backward linkages), in case of Indonesia it is driven by resource availability (forward linkages). So far, China is the largest nickel consumer and according to statistical data, China's demand for nickel in 2020 has reached 1.31 million tonnes.

To explore the extent of value addition through refining and processing, it is important to note that currently, nickel continues to be a stainless-steel driven market. To serve the EV battery industry, nickel sulphate (Ni_2SO_4) (often referred as Class 1) is required. Any high-purity nickel metal unit, many of which are currently produced from laterites, can be dissolved in sulphuric acid to form nickel sulphate upon evaporation. However, the process to sulphate from sulphide ore is more direct and generally lower cost, while the need to utilise difficult-to-process laterite ores drive some nickel sulphate premium over LME (London Metal Exchange) nickel through the cycle, thereby reducing the extent of value addition for LCTs. As a result, only 5% of nickel currently goes into batteries, and less than 1% into EV batteries. This is well below the levels for lithium (42%, 25%) and cobalt (55%, 10%). However, EV batteries are forecast to account for 20% of total refined nickel usage by 2025.

Figure 17: A simplistic representation of the value chain stages of nickel



Source: Authors' representation based on (CRU, 2019; Talon Metals Corp, n.d.)

As a result, given a near non-existent market the extent of value addition in nickel smelting/refining for LCTs is difficult to assess.

6.6 Manufacturing and Use

Nickel is widely used in hybrid and electric vehicle batteries, including nickel-cadmium and nickel-metal hydride batteries. Nickel is an essential raw material used in the manufacturing of electrolysers. Two technologies are most prominent in the installed electrolysers capacity: Alkaline Electrolysers (AEL Units) and Proton Exchange Membrane (PEM) electrolysers. In 2021, 70% of the global installed capacity of electrolysers was covered by AEL units, whereas PEM electrolysers accounted for 25% of the installed capacity (IEA, n.d.). Solid Oxide Electrolysis Cell (SOEC) has introduced a new wave in electrolyser technologies. SOEC and other emerging technologies like Anion Exchange Membranes (AEM) electrolysis are in their nascent stage of commercial viability and are not matured compared to the AEL or PEM electrolysers. The future of installed capacity by 2030 will likely be split equally between AEL or PEM electrolysers, wherein there will also be various other technological advancements.

Table 10 Characterisation of four types of water electrolysers

	Alkaline (AEL)	PEM	AEM	Solid Oxide (SOEC)
Operating temperature	Alkaline 70-90 °C	PEM 50-80 °C	AEM 40-60 °C	Solid Oxide 700-850 °C
Operating pressure	1-10 bar	< 70 bar	< 35 bar	1 bar
Electrolyte	Potassium hydroxide (KOH) 5-7	PFSA membranes	polymer support with KOH or $NaHCO_3$ 1molL-1	Yttria-stabilised Zirconia (YS!)
Electrode catalyst (oxygen side)	Nickel-coated perforated stainless steel	Iridium oxide	High surface area Nickel or NiFeCo alloys	Pero skite-type (E.g. LSCF, LSM)
Electrode catalyst (hydrogen side)	Nickel-coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni/YSZ
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated Stainless steel	Coha I t-coated stainless steel

Source: (IRENA 2020)

As shown in Table 10, PEM technology can operate under much higher pressure than AEL technology. Although recent advancements in AEL technology have reduced its performance gap compared to PEM, PEM technology still requires specific materials, such as titanium and noble metal catalysts, for long-term use, making it more expensive than alkaline electrolysers (IRENA 2020). On the other hand, SOEC (Solid Oxide Electrolysis Cell) technologies are currently limited to kilowatt-scale applications and are not yet scalable to 1 megawatt. AEM (Anion Exchange Membrane) technology, while showing promise and having benefits comparable to both alkaline and PEM technologies, is still in the early stages of commercial use and requires further development to meet performance standards for stable, long-term operation.

Globally, alkaline technology remains the most cost-effective option, with an average cost ranging from US$ 700 to US$ 1,100 per kW. PEM technology, the next best alternative, averages between US$ 1,200 and US$ 2,000 per kW. Efficiency is a critical consideration, with alkaline electrolysers operating at approximately 70% efficiency, producing 0.021 kg of H2 per kWh, while PEM technology operates at around 60% efficiency, producing 0.018 kg of H2 per kWh (McKinsey 2023b). It is anticipated that with ongoing advancements, PEM technology could become competitive with alkaline electrolysers by FY 2030.

The manufacturing of PEM electrolysers involves materials such as iridium, platinum, gold, and titanium, which are emission-intensive and scarce, contributing to their higher cost. In contrast, alkaline electrolysers primarily use nickel, which is more abundant and less costly, making them 50% to 60% cheaper than PEM electrolysers (Raj, Lakhina, and Stranger 2022).

In India, alkaline electrolysers are mainly used in the chlor-alkali industry to produce chlorine and sodium hydroxide. The current electrolyser capacity in the country is estimated to be less than 1 GW. India's hydrogen demand is currently fulfilled by international manufacturers (Raj, Lakhina, and Stranger 2022). Although the domestic electrolyser manufacturing market is still in its early stages, there have been technological advancements by indigenous groups, indicating a positive outlook for future development.

6.7 Supply Challenges and Growth Prospects for Leading Producers

In the Net Zero Emissions Scenario, there's a notable gap of over 25% between the anticipated demand and supply of nickel. This gap widens to 60% for nickel sulphate production, crucial for batteries, signalling a substantial shortage of processed nickel products (International Energy Agency 2021).

China: It contributes to about 25% of global Class I nickel production. as of 2020, is the largest nickel consumer worldwide. Relying heavily on imports to meet its demand due to inadequate domestic production, China primarily sources its nickel from the Philippines and Indonesia. In 2021, a significant 89.6% of China's total nickel ore imports came from the Philippines. China's current imports from Indonesia mainly take the form of intermediate nickel due to the aforementioned Indonesia's raw nickel export ban. Chinese investment in Indonesia's nickel production has surged, surpassing investments from other countries by a significant margin. In the past decade, Chinese companies have poured $14.2 billion of investment into nickel production in Indonesia. In comparison, the combined total investment from Australia, Canada, and South Korea is just $1.5 billion (Ho and Listiyorini 2022). China aids Indonesia's shift from stainless steel processing to mixed hydroxide precipitate production through the provision of labour, materials, and technology.

Indonesia: Boasting the world's largest nickel reserves and production, Indonesia has prioritised enhancing domestic processing capabilities in recent years. With export bans on nickel ore, Indonesia has attracted substantial Chinese investment to bolster its nickel processing capabilities. The country aims to increase the number of operating nickel smelters, targeting over 30 by 2023. However, Indonesia faces challenges in mass-producing battery-grade nickel due to its ore composition. To address this, the High Pressure Acid Leach (HPAL) technique has been adopted, allowing for the production of higher-purity Class 1 nickel, albeit with environmental implications (Ribeiro, Holman, and Tang 2021).

Nickel production in Indonesia is concentrated in Sulawesi, particularly in the Indonesia Morowali Industrial Park (IMIP), a major hub for nickel-based industries. Two HPAL projects by Chinese companies began operations in 2022, while another site, the Indonesia Weda Bay Industrial Park (IWIP), saw early production in 2020.

Indonesia is set to play a significant role, contributing nearly half of the global nickel production growth from 2021 to 2025. The success of its High Pressure Acid Leach (HPAL) projects hold paramount importance for the future global nickel supply, especially for battery production. From a geopolitical perspective, Indonesia stands poised to emerge as a major supplier of battery-grade nickel, particularly given the uncertainties surrounding Russia's nickel production due to the Ukraine conflict. Currently, Russia accounts for 17% of the global production capacity for Class I nickel used in battery production, but potential sanctions could further disrupt the supply chain.

Philippines: The Philippines, the second-largest nickel ore producer globally, supplies a significant portion of China's nickel ore imports. Following Indonesia's export ban in 2020, the Philippines has become China's primary nickel ore supplier. The Philippines government is considering potential export restrictions on nickel ore, taking cues from Indonesia's policies (Chen 2023).

Russia: The world's third-largest nickel producer has notably impacted the nickel market due to its invasion of Ukraine. Holding 11% of global nickel production and 15% of world nickel exports, Russia's actions have disrupted the European Union's nickel supply chain, leading to a decrease in Russian nickel imports by EU countries. Finland's import share from Russia stands at 84%, while the figures for the Netherlands and Ukraine are 34% and 23% respectively. Despite the European Union not imposing sanctions on Russian nickel exports, the share of Russian nickel in the EU supply chain has seen a significant decrease, dropping by 20% year on year for the first quarter of 2023. Currently, Russia accounts for 17% of the global production capacity for Class I nickel used in battery production, but potential sanctions could further disrupt the supply chain. Amidst the EU's reduced imports from Russia, there has been a notable increase in imports from the U.S. and Australia. European buyers are distancing themselves from Russian nickel, prompting Norilsk Nickel, Russia's top miner, to contemplate reducing nickel output by approximately 10% in 2023 (Bloomberg News 2022). Additionally, there are discussions of shifting export focus to China by selling nickel in yuan at prices determined in Shanghai. Meanwhile, Indonesia's burgeoning nickel investment landscape has spurred active market activities, with the total proceeds from nickel mining and processing companies' Initial Public Offerings (IPOs) in the first quarter of 2023 surpassing the combined amounts raised in 2022 and 2021.

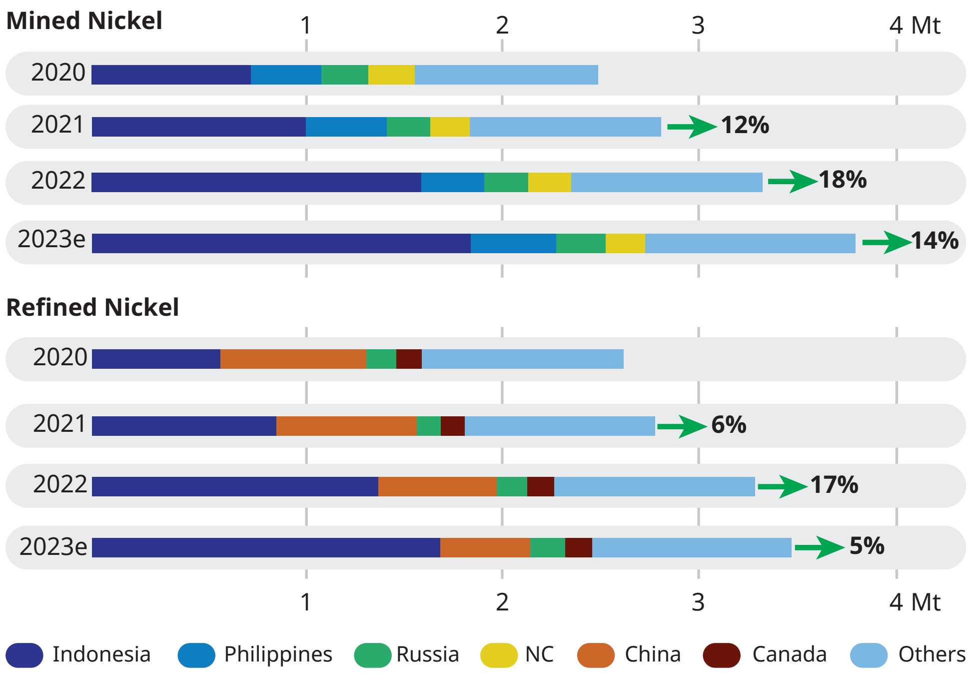
6.8 Investments in Mining and Processing

The demand for nickel is surging, fuelled by its growing use in electric vehicle batteries. This has sparked a significant increase in investment activity across the nickel sector. In 2022, global investments in nickel mining and processing projects exceeded $10 billion. The majority of these investments have been directed towards Indonesia and Australia, which possess the world's largest nickel reserves, as well as the Philippines, which has robust nickel processing facilities. The focus of these investments is on developing new mines and expanding existing operations.

This trend is expected to continue in the coming years, driven by several factors including increasing demand for nickel from the electric vehicle industry, the geographical concentration of nickel suppliers, rising nickel prices, the potential for nickel to be used in other applications, such as fuel cells and wind power, which is boosting investor confidence due to the anticipated growth in demand for these technologies in the future. To meet the projected nickel demand by 2035, an additional 72 mines need to be built (Atkins 2023). Furthermore, approximately $66 billion in investments is required to produce battery-grade nickel by 2030 (Benchmark Mineral Intelligence 2023).

Global refined nickel consumption is forecast to grow to 3.2 Mt in 2023 — an increase of 9.3% year-on-year. Corresponding to this, refined nickel output is expected to reach 3.3 Mt in 2023 (7.6% growth year-on-year), 3.5 Mt (5.8%) in 2024 and 3.6 mt (3.9%) in 2025 (Department of Industry, Science and Resources, Commonwealth of Australia, 2023).

Figure 18: Growth trend in nickel refining over the last four years



Source: (International Energy Agency 2023)

Box 1: Indonesia's 360° approach to nickel refining

Over the last three years, there has been a major shift in nickel refining. Riding on the back of the Indonesian government's decision to ban nickel ore exports, the country has overtaken China as the largest refined nickel producer, although many of the new facilities are financed by Chinese companies. While there are contesting views, it is largely agreed that the export ban compelled nickel mining companies and processors to build smelters locally in Indonesia, thereby leading to local value addition and jobs.

Further, many of Indonesia's new refining facilities are now using the high-pressure acid leaching (HPAL) method to process its laterite resources into Class 1 products and exploring ways to convert nickel pig iron into nickel matte which can be further refined into battery-grade nickel (International Energy Agency 2023). The country is also looking to capture downstream value through co-location. A unit of CATL is set to join local state-owned groups in Indonesia to build USD 6 billion mining-to-batteries complex which will include nickel mining and processing, battery materials, recycling, and battery manufacturing facilities. A consortium led by LG Energy Solution, the world's second largest EV battery maker, also announced plans to invest USD 9 billion in the entire EV battery value chain in Indonesia, including smelting and refining of nickel, and manufacturing cathode materials.

6.9 Key companies involved in the supply chain

Despite the EV-battery excitement, in 2020, 74 percent of the market was still driven by the stainless-steel industry, while batteries represented only 5 to 8 percent of demand.

The largest Nickel producing companies include Nornickel (Russia), Vale (Brazil), Glencore (Switzerland), BHP (Australia), Anglo American (UK), South32 (Australia), Eramet (France), IGO (Australia), Terrafame (Finland) and MCC (China).

In recent years, the emerging nickel projects in Indonesia have predominantly taken the form of joint ventures led by Chinese companies. This trend arose following the nickel ore ban, compelling Chinese firms to transfer their High-Pressure Acid Leach (HPAL) expertise, thereby accelerating Indonesia's efforts to build domestic processing capabilities. Notably, several major HPAL plants in Indonesia involve Chinese companies, providing essential HPAL technologies and skilled labour support. For instance, in 2022, Brazilian nickel miner Vale announced two HPAL projects in Indonesia in partnership with China's Zhejiang Huayou Cobalt. Currently, three operational HPAL plants in Indonesia rely on Chinese investment.

In the wake of the electric vehicle (EV) boom, fuelled further by the U.S. Inflation Reduction Act (IRA), numerous American EV manufacturers have initiated investments in Indonesian nickel projects to secure their nickel supply for batteries. For instance, Tesla sealed a $5 billion deal to procure nickel from Indonesia, while Ford engaged in a joint venture worth $4.5 billion to process nickel in Indonesia. Concurrently, Indonesia is actively working on proposing a limited free trade agreement with the U.S., aiming to enable Indonesian businesses to capitalise on the tax credits available through the U.S. IRA. This initiative mirrors the recently concluded agreement with Japan and the ongoing negotiations with the EU.

6.10 Pricing and Markets

Nickel prices historically mirror those of other base metals like copper and are heavily influenced by global economic growth and the state of the world economy. This is because nickel finds extensive use in construction, especially in stainless steel production. With the growing demand for nickel in energy transition technologies, particularly for high-purity nickel in batteries (also used in stainless steel), the importance of nickel has surged. In 2022, approximately 10% of the demand for nickel came from EV batteries, marking a significant increase compared to the 2% share observed just five years earlier.

Recent price fluctuations in the nickel market have been predominantly driven by geopolitical events, such as the Russian invasion of Ukraine, and shifts in the industrial policies of various countries. In February 2022, nickel prices experienced extreme turbulence, with trading activity surging by 250% and prices skyrocketing by $30,000 within minutes. This sudden price surge was sparked by concerns over potential sanctions on Norilsk Nickel, a major Russian nickel producer, coinciding with a substantial bet by Tsingshan, the world's largest stainless-steel producer, on falling prices.

Overall, in 2022, the supply of nickel outpaced demand due to increased output from Indonesian smelters and a slowdown in global stainless-steel demand. This has somewhat alleviated concerns about the supply of Class 1 nickel. Despite a decrease from peak levels in early 2022, nickel prices remain elevated compared to pre-pandemic levels. Forecasts suggest that battery-grade nickel may continue to face tight supply in the years ahead.

Projections indicate that the nickel market could encounter a structural deficit by 2028, with increasing demand and limited new supply. This could lead to a faster price increase in 2028, driven by rising demand for nickel in EV batteries. Output from Indonesia is expected to help relieve some price pressure by converting lower-grade Class 2 nickel into higher-grade Class 1 nickel suitable for the battery industry.

However, despite the growing number of nickel projects in development, ramping up production is a time-consuming process. For example, HPAL nickel production projects in Indonesia historically take around five years to achieve nominal production levels. This extended timeline for project development introduces uncertainties regarding when these projects will come online, thereby impacting the future price of nickel.

Indonesia is poised to play a critical role in global nickel production growth from 2021 to 2025. The success of its HPAL projects is vital for future nickel supply, especially for battery production. With geopolitical uncertainties surrounding Russia's nickel production due to the Ukraine conflict, Indonesia is positioned to become a major supplier of battery-grade nickel. Currently, Russia accounts for 17% of global production capacity for Class 1 nickel used in battery production, but potential sanctions could further disrupt this supply chain.

6.11 Agreements and Contracts

Refer Agreements and Contracts in section 3.9 of Volume II.

6.12 Recycling

Nickel recycling is predominantly conducted through pyrometallurgical recovery, an intermediate process that precedes the final extraction and refining stages at hydrometallurgy facilities. The primary advantage of the pyrometallurgical phase is its ability to eliminate undesirable materials such as electrolytes (which contain fluorine), phosphorus, graphite, and plastics. This results in a metal alloy with significantly fewer impurities, enhancing the performance and efficiency of the subsequent hydrometallurgical processes. Consequently, the overall metal recovery efficiency is typically high, exceeding 90%, due to the reduced presence of impurities.

6.13 Nickel Consumption and Production in India

India has relatively modest nickel reserves, with limited domestic production primarily from the Sukinda Valley in Odisha, known for its lateritic nickel ores. Major suppliers of nickel to India include Indonesia, Russia, Canada, and Australia.

Nickel is not produced from primary sources in India, and the entire demand, estimated at 45 kilo tonnes per annum, is met through imports. The nickel, copper, and acid recovery plant at Hindustan Copper Limited's (HCL) Indian Copper Complex (ICC) in Ghatshila, Jharkhand aims to produce LME (London Metal Exchange) grade nickel metal, making it the first unit of its kind in India. Initially, the plant's capacity is set at 50 tonnes per annum, based on current production from the Surda mines. The nickel output is expected to increase nearly eightfold after completing mine expansion projects at Ghatshila. However, no production has been reported from this project in recent years.

In the private sector, Vedanta Resources has acquired Nicomet Industries Ltd (NIL), a leading nickel and cobalt producer in Goa. NIL, located in Goa, currently produces nickel metal and derivatives with an annual production capacity of about 5,400 metric tonnes per annum, according to the (Indian Bureau of Mines 2023c). Nicomet has emerged as a certified producer of high-quality battery-grade nickel sulphate crystals used in manufacturing EV batteries globally.

7

SILICON

7 SILICON

7.1 Natural Occurrence

Silicon (Si) constitutes 27.7% of the Earth's crust by mass, making it the second most abundant element after oxygen. Common examples of silicon oxide include sand, quartz, rock crystal, amethyst, agate, flint, and opal. Silicate materials encompass asbestos, granite, hornblende, feldspar, clay, and mica. Silicon commonly exhibits an oxidation state of 4 and -4 and occurs in isotopic forms (28Si, 29Si, 30Si).

Silicon occurs naturally as quartz (SiO2) and silicates. High-purity quartz, often containing impurities like oxides of Fe, Al, K, Ca, and Na, is the raw material for producing metallurgical grade silicon (MGS). High-quality quartz is mined from riverbeds and quartz veins, and enrichment techniques such as milling, washing, size classification, gravity and magnetic separation, and acidic leaching are used to achieve the desired purity.

Metallurgical Grade Silicon Production: MGS is produced via carbothermic reduction, using a blend of powdered SiO2, coke, coal, charcoal, and wood chips. This blend undergoes reduction in a submerged-arc electric furnace at around 2000°C, resulting in molten Si, which is then refined, cooled, solidified, and crushed to achieve 98.5 – 99.5% pure Si.

Solar Grade Silicon Production: MGS, containing impurities like Al, Fe, and Ca, is refined using the Siemens process. This involves:

- Fine MGS particles fluidised with hydrochloric acid (HCl), in the presence of a catalyst.
- Distillation of the resulting chlorosilane (SiHCl3) to obtain pure $SiHCl_3$.
- Chemical vapor deposition (CVD) of ultrapure Si in a Siemens reactor, reducing $SiHCl_3$ with H_2 gas at over 1100°C to produce 99.99999% pure polycrystalline Si (Solar Grade Si) (Xakalashe and Tangstad 2011).

An alternative, energy-efficient process involves the continuous deposition of pure Si granules in the fluid bed reactor (FBR). (Chalamala 2018)

Mono-crystalline Silicon: Preferred for the electronics industry, produced using the Czochralski process. Polycrystalline Si is melted under vacuum and solidified on a rotating mono-crystalline Si seed, forming a cylindrical ingot over a two-day production cycle.

Multi-crystalline Silicon: Used in the photovoltaic (PV) industry**,** produced using the Bridgman process. In this process, polycrystalline Si is melted and crystallised in the form of a block with controlled cooling rates, temperature gradient and growth rates to obtain high-quality crystal structure (Xakalashe and Tangstad 2011). These processes illustrate the comprehensive steps required to transform natural quartz into various forms of high-purity silicon for different industrial applications.

7.2 Resources

There is an abundance of global resources for producing silicon metal and alloys, sufficient to meet world requirements for many decades. However, quantitative estimates are not available. The primary source of silicon is silica in various natural forms, such as quartzite (USGS 2023).

7.3 Production & Reserves

China, Russia, Norway, and Brazil are the leading producers of silicon, as shown in Table 11. In 2022, China alone accounted for nearly 68% of the global silicon production. However, the production of steel, the primary application for ferrosilicon, declined by 4% compared to 2021. This decline was due to supply chain disruptions from the Russia-Ukraine conflict and intermittent lockdowns in China due to the COVID-19 pandemic. While silicon reserves are ample in most major producing countries relative to demand, there are no quantitative estimates available. Table 11 presents the estimated production numbers for the major producers of silicon, including both ferrosilicon and silicon. Ferrosilicon is produced in two grades: 50% silicon and 75% silicon.

Table 11: Silicon production and reserves data (2022)

Country	Mine Production		Reserves
	2021	2022	
United States of America	313,000	310,000	"The reserves in most major producing countries are ample in relation to demand. Quantitative estimates were not available."
Australia	50,000	50,000	
Bhutan	85,000	85,000	
Brazil	389,000	400,000	
Canada	49,000	49,000	
China	6,400,000	6,000,000	
France	127,000	120,000	
Germany	63,000	63,000	
Iceland	111,000	110,000	
India	59,000	59,000	"The reserves in most major producing countries are ample in relation to demand. Quantitative estimates were not available."
Kazakhstan	122,000	120,000	
Malaysia	85,000	92,000	
Norway	362,000	360,000	
Poland	49,000	49,000	
Russia	644,000	640,000	
Spain	60,000	57,000	
Ukraine	49,000	19,000	
Other Countries	128,000	210,000	
Total	9,150,000	8,800,000	

Source: (USGS 2023).
Data in metric tonnes.

7.4 Processing

Silicon is a critical component in various electronic equipment and solar modules essential for the green transition. Two grades of silicon are mainly used by manufacturers, electronic-grade silicon (high purity) and solar-grade silicon (lower purity). Both these grades of silicon are recovered from metallurgical-grade silicon (Sati, Powell, and Tomar 2022). Silicon is often naturally present in silicon dioxide or silica (SiO_2), known as quartz. An essential process is the reduction of SiO_2 to extract silicon (Si) from the ore. The reduction process decreases the number of oxidants by charging the electrons with further purification methods. The most widely used technology for the reduction of SiO_2 is Carbothermal reduction (A. Gupta 2022).

While the carbothermal reduction process was invented in the nineteenth century, it remains the most prominent technology. This reduction process requires large quantities of graphite carbon to convert the quartz to Si in electric arc furnaces. Additionally, arc furnaces that extract Si require about 14-16 kWh/kg of energy (PVEducation, n.d.). Higher energy is consumed in extracting purer grades of Si for Solar Cells in the form of polysilicon. The carbothermal process has often been criticised for emitting gases containing large quantities of dust (Yolkin et al. 2020). Replacing carbon with silicon carbide has shown the potential to reduce energy consumption and increase the productivity of furnaces. Silicon carbide also produces less dust with reduced emission of gases.

In 2022, China accounted for about 70% of global silicon processing capacity. The top producers of silicon metal, in descending order, are China, Russia, Norway, and Brazil, where quartzite is directly processed into ferrosilicon and silicon metal. The EU and the US have very limited silicon refining capacity, and Australia also processes very little (USGS 2023).

7.5 Manufacturing and Use

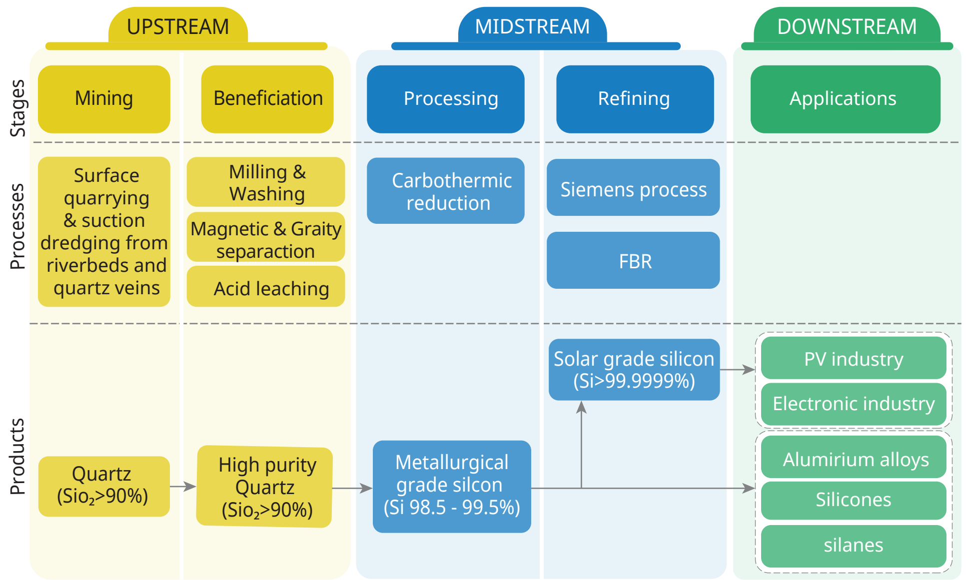
Silicon metal plays a pivotal role in various industrial applications, including the manufacturing of aluminium alloys, solar cells, and semiconductors. A large portion is utilised in alloy production, such as ferro-silicon (iron-silicon) and aluminium-silicon, crucial for deoxidising steel and manufacturing machine tools, cylinder heads, engine blocks, and components for transformers and dynamos. In clean energy technologies, hyper-pure silicon serves as a semiconductor in solid-state devices. To modify its electrical properties, silicon is selectively doped with trace amounts of boron, gallium, phosphorus, or arsenic.

Polysilicon manufacturing is a capital and energy-intensive process. The solar cell itself is at the heart of the silicon PV value chain. Passivated Emitter Rear Solar Contact (PERC) solar cells are the most commonly used form of cells globally. International Technology Roadmap for Photovoltaic (ITRPV), in its 13th edition, 2022, predicted that PERC and PERC-like cells will continue to dominate the market in the coming years (exceeding 80% by 2025) (Bhambhani 2023a). In 2023, the ITRPV estimates stated that cells based on silicon heterojunction technology (HJT) and Tunnel oxide passivated contact (TOPCon) would account for 19% and 60% of the market share by 2033. TOPCon is an improved variant of the PERC technology.

Each of the solar cell technologies discussed above has varying capital expenditures. The leading technology, PERC, is estimated at ~USD 22 million/GW, while cost expenditure for TOPCon is ~USD 30 million/GW) and for HJT, it is ~USD 55 million/GW (Shiradkar et al. 2022).

7.6 Supply Challenges and Growth Prospects for Leading Producers

Figure 19: A simplistic representation of the value chain stages of silicon



Source: Authors' representation based on (US Department of Energy 2022; Bide et al. 2020; Elghniji et al. 2020; Xakalashe and Tangstad 2011)

The production of silicon metal involves a complex and interconnected supply chain, from raw material extraction to end-user industries. As demand for silicon metal continues to rise, ensuring a stable and reliable supply chain has become increasingly important. Challenges within the silicon metal supply chain can arise from factors such as raw material sourcing, refining processes, transportation logistics, market dynamics, and global economic influences. Addressing these concerns is essential to meet the growing demand for silicon metal and to support the industries that depend on this critical resource.

7.7 Investments in Mining and Processing

Recent years have seen a substantial surge in investments in silicon metal production. Establishing a medium-sized quartz sand beneficiation plant typically requires capital ranging from 1 to 5 million USD (Shirley 2023). In 2022 alone, global investments in silicon metal projects exceeded 2 billion USD, driven by rising demand, increasing scarcity, and the need to secure long-term supplies. Start-ups focused on commercialising silicon materials for battery anodes raised over 0.5 billion USD during the same period (Blois 2022).

While most silicon metal investments are still concentrated in China, there is growing interest in projects across the United States, Europe, and India. This global surge in investment is a positive development, helping to ensure an adequate supply to meet escalating demand. However, the silicon metal market remains volatile, and there is a potential risk of sharp price increases in the future. Silicon metal, essential for aluminium alloys, solar cells, and semiconductors, is expected to see increased demand as these industries expand.

7.8 Key Players involved in the supply chain

The largest global manufacturers of silicon metal include Ferroglobe Plc (US), Dow DuPont (US), Elkem ASA (Norway), RIMA Group (Italy), Rusal, LIASA, (Russia) and Wacker Chemie AG (Germany).

The challenges in the silicon supply landscape, combined with the future growth prospects of leading producers, stem from the geographical concentration of silicon metal production. To address this, manufacturers are strategically planning to expand global production capacity, aiming to introduce an additional 0.5 to 1 million tonnes (MT) worldwide by 2025. China is expected to account for over 50 percent of this capacity growth, with Europe, the US, and other regions also contributing (Aranca 2023).

Capacity Expansion Plans of companies:

- Ferroglobe has restarted its second furnace for silicon production at its Selma facility in Alabama, USA, with an annual capacity of 22,000 MT (Ferroglobe 2022).
- Daqo New Energy, a Chinese polysilicon producer, plans to add 180,000 to 220,000 MT/year of polysilicon capacity by the end of 2023 (Norman 2022).
- TBEA Co aims to increase its polysilicon output from 110,000-120,000 MT in 2022 to 240,000-250,000 MT in 2023 (Shaw 2022).
- GCL Technology is collaborating with TCL to establish a polysilicon production base in Hohhot, Inner Mongolia, aiming for 10,000 MT of polysilicon and 100,000 MT of granular silicon within the next few years (EnergyTrend 2021).
- Wacker Chemie AG plans to expand silicon production capacity in Norway, expected to be completed by 2025 (Diermann 2022).
- Emirates Global Aluminium (EGA), based in the UAE, has initiated a project to manufacture silicon metal domestically, aiming to meet its annual demand of approximately 60,000 MT (The National 2022).

7.9 Pricing and Markets

Silicon has exhibited significant price fluctuations in recent years, primarily due to production cuts in China, a major global producer. In 2019, China accounted for nearly 64% of global silicon production (USGS 2023). Seasonal factors and electricity curbs in Yunnan province, which produces about 20%

of China's silicon, have driven prices higher. In 2021, the Yunnan Provincial Development and Reform Commission limited local industrial silicon output to 10% of August levels from September to December (Shanghai Metals Market, 2021). Furthermore, industrial silicon output from January to August saw a year-on-year decline of 18%, approximately 249,000 metric tonnes (Shanghai Metals Market, 2021), delaying new production facilities in Yunnan in 2022 and globally increasing silicon prices, which impacted the production of automotive parts and electronics.

The prices of silicon metal, essential for industries such as semiconductors, solar, and aluminium alloys, have shown significant volatility in recent years. Between 2021 and 2022, silicon metal prices surged to three to four times their 2020 levels due to limited supply and increased demand. The energy-intensive nature of silicon metal production, combined with energy rationing in China and rising energy costs in Europe, adversely affected global supplies. Additionally, growing demand for silicon metal in applications like solar cells contributed to the price surge. However, prices began to decline in the fourth quarter of 2022, dropping by 60 to 70 percent in the last two quarters due to improved supply and weakened demand, although demand from the solar industry partially offset this decline (Aranca 2023). Throughout 2022, silicon prices increased at a slower rate, and various market surveys predicted a decline in 2023, which has so far been accurate (IEA 2023).

China, as the largest producer of silicon metal, significantly influences the global supply of this resource. From 2019 to 2020, silicon prices saw a substantial increase of up to 300 percent (Chia, Murtaugh, and Burton 2021). This price surge, along with supply chain challenges and power shortages, posed significant difficulties for manufacturers and consumers of silicon-based products. Consequently, many Norwegian manufacturers and other companies producing silicon-based goods had to temporarily halt certain sales operations. Throughout most of the 2000s, silicon prices fluctuated between approximately USD 1,200 and USD 2,600 per tonne.

The silicon shortage has also significantly impacted the solar industry, which uses a purified and refined variant of silicon in photovoltaic panels. Supply reductions caused the price of solar-grade polysilicon to rise by 13 percent in 2021, reaching its highest level since 2011. Since mid-2020, the price of polysilicon has escalated by over 400 percent (Chia, Murtaugh, and Burton 2021), with the price of PV-grade polysilicon more than quadrupling since early 2020 (IEA 2021).

7.10 Agreements and Contracts

a) Mining companies often secure funding through offtake agreements well before a project begins, boosting investor confidence. Headquartered in Norway, REC Silicon, a global supplier of advanced silicon materials, entered a 10-year offtake agreement with Hanwha Solutions to supply high-purity granular polysilicon from REC's Moses Lake Facility in the USA (Bhambhani 2023b). This facility, shut down in 2019 due to tariffs from the US-China trade dispute, hopes to restart operations with support from the Solar Manufacturing for America Act (SEMA) and a pre-payment from Hanwha Solutions, which holds a 33.3% stake in REC Silicon (The Spokesman-Review 2019; REC Silicon ASA, n.d.).

b) Private equity funds are increasingly investing in CETMs projects using various contracting methods like streaming and offtake agreements (Kinch 2022). For example, in 2015, PCC SE of Germany contracted with Iceland's Bakkastakkur slhf to finance planned silicon metal production in Iceland, securing USD 300 million for 15 years (CMS 2015). PCC SE engages in the production of chemical feedstock and silicon. Bakkastakkur comprises of over ten pension fund companies and Islandsbanki, an Islandic commercial bank (PCC SE, n.d.).

c) Price conditions in the market also drive private equity investment. JinkoSolar, a leading silicon technology company in China, announced in June 2021 a USD 48.64 million equity investment in Inner Mongolia Xinte

Silicon Materials Company to support an annual capacity of 100,000 tonnes of polysilicon, giving JinkoSolar a 10% stake in Xinte Silicon (Jink Solar, n.d.; MERCOM, n.d.).

7.11 Recycling

Silicon recycling involves reclaiming and reprocessing silicon materials from various waste sources, notably electronics and solar panels. Recycling silicon helps conserve natural resources by reducing the need for virgin silicon production, which requires significant energy and raw materials. Silicon is recycled by dismantling, crushing, chemical and physical separation, smelting and refining and casting and re-crystallisation. Recycling faces challenges like technical complexity and economic viability. Innovations in chemical processes, automation, and circular economy models are improving the efficiency and feasibility of silicon recycling, However, high-tech applications require extremely pure silicon, which can be challenging to achieve with recycled material.

7.12 Silicon Consumption and Production in India

India has significant reserves of quartz, which is the primary source of silicon. Major quartz deposits are found in the states of Rajasthan, Andhra Pradesh, Karnataka, and Tamil Nadu. Despite having substantial quartz reserves, India has limited production of silicon metal. Most of the silicon used in the country is in the form of silicon wafers, alloys, and other compounds rather than pure silicon metal. Increasing investment in technology and infrastructure is crucial for boosting domestic silicon production.

The anticipated high production costs of silicon metal are likely to serve as a barrier to new entrants such as India. The energy-intensive nature of producing silicon metal through arc furnaces contributes to its elevated production costs. Industrial electricity rates in India do not necessarily align with affordability, and this is significant given that a substantial portion of the total production expenses are linked to energy consumption. Additionally, the cost of silicon metal production is influenced by factors like the prices of coal, quartz, oil, natural gas, and electrodes. The concentration of quartz mining among a limited number of players indicates that India is unlikely to emerge as a significant silicon-producing and exporting nation in near future. However, the Production Linked Incentive schemes in solar PV manufacturing have provided initial impetus for domestic processing of silicon and with support from industry, the domestic value chain can be built and strengthened over time.

Solar installations in the country primarily use Photovoltaic (PV) technology. It is estimated that 339-395 GW of solar PV will be deployed in India by 2040 (Sharma, Mahajan, and Garg 2024). For 2022, India had set an estimated target of deploying 100 GW of solar power (Press Information Bureau 2020). The domestic cell and module manufacturing capacities reached approximately 4.7 GW and 39 GW, respectively at the end of 2022 (Joshi 2023).

Provisions for low-cost financing and cheaper electrical power are required to promote polysilicon manufacturing in the country (Verma and Dr. Kumar 2018). India has no manufacturing capacity to domestically set up the photovoltaic (PV) value chain, such as manufacturing polysilicon wafers (Gulia et al. 2022). Indian solar panel manufacturers mainly import polysilicon wafers from China.

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