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NITI Aayog

Mine to market: critical minerals supply chain for domestic value addition in lithium-ion battery manufacturing

June 2023

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Foreword

Advanced chemistry cell (ACC) batteries are the bed rock of future low carbon transportation and energy systems. India's domestic ACC battery manufacturing industry is fast emerging with support from government initiatives on both demand and supply side. Critical minerals supply chain, especially lithium, cobalt, nickel and spherical graphite, refining for active materials are vital to achieve domestic value addition in the manufacturing of ACC battery electrodes. By localizing the mining and refining value chain of critical minerals, India can reduce its reliance on imports and help build resilience in global supply chains.

NITI Aayog has been studying the mine to market landscape of critical minerals and active materials used in the production of lithium-ion batteries (LIB). As global demand for lithium-ion batteries continues to rise, India has a unique opportunity to support resilient supply chains of critical minerals, establish self-reliance and reduce imports. Some developed countries have combined demand side incentives for consumers and businesses to purchase clean vehicles with programs to expand domestic manufacturing and sourcing of critical minerals and battery components. In these countries, the battery's critical minerals must meet certain requirements for sourcing or processing domestically for eligibility of EV demand side incentives.

India has become the newest partner in the US led Mineral Security Partnership (MSP) to bolster critical mineral supply chains. The partnership aims to accelerate the development of diverse and sustainable critical mineral supply chains. Apart from this, G2G dialogues are advancing with friendly countries for joint exploration and mining. Government of India has set up KABIL to ensure a consistent supply of critical and strategic minerals through G2G negotiations and acquiring mining assets abroad.

This report provides useful information and insights to policymakers, industry, investors, partners and stakeholders in the ACC battery and critical minerals ecosystem. The report may serve as a catalyst for transformative change and drive India's sustainable development agenda forward. We are confident that it will lay a foundation for informed decision-making and enable stakeholders to capitalize on the immense opportunities presented by the localization of the ACC battery value chain in India.

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Executive Summary

A thriving domestic lithium-ion battery (LIB) manufacturing industry will need resilient supply chains of critical minerals and raw materials, such as lithium (Li), nickel (Ni), cobalt (Co) and spherical graphite to manufacture key LIB components and boost domestic value addition.

The first two chapters in the report provide in-depth analysis of the bill of materials for manufacturing LIBs, demand outlook for critical minerals and raw materials essential for supporting domestic value addition. A status quo analysis of the current landscape of critical mineral reserves, production, refining capacity, trade statistics and market participants is drawn from the Indian Minerals and trade statistics published by relevant authorities.

In subsequent chapters, the report provides an international perspective of critical minerals processing / refining technologies for production of battery grade raw materials and chemical precursors (viz. Li_2CO_3, LiOH, $NiSO_4$, $CoSO_4$ and Spherical Graphite) that are critical for domestic value addition. The bill of ancillary chemicals, energy and emissions footprint typically involved in the domestic production of these critical minerals is analyzed. The report also provides techno-economics of critical minerals extraction, global reserves and capital projects in pipeline for critical mineral commodities.

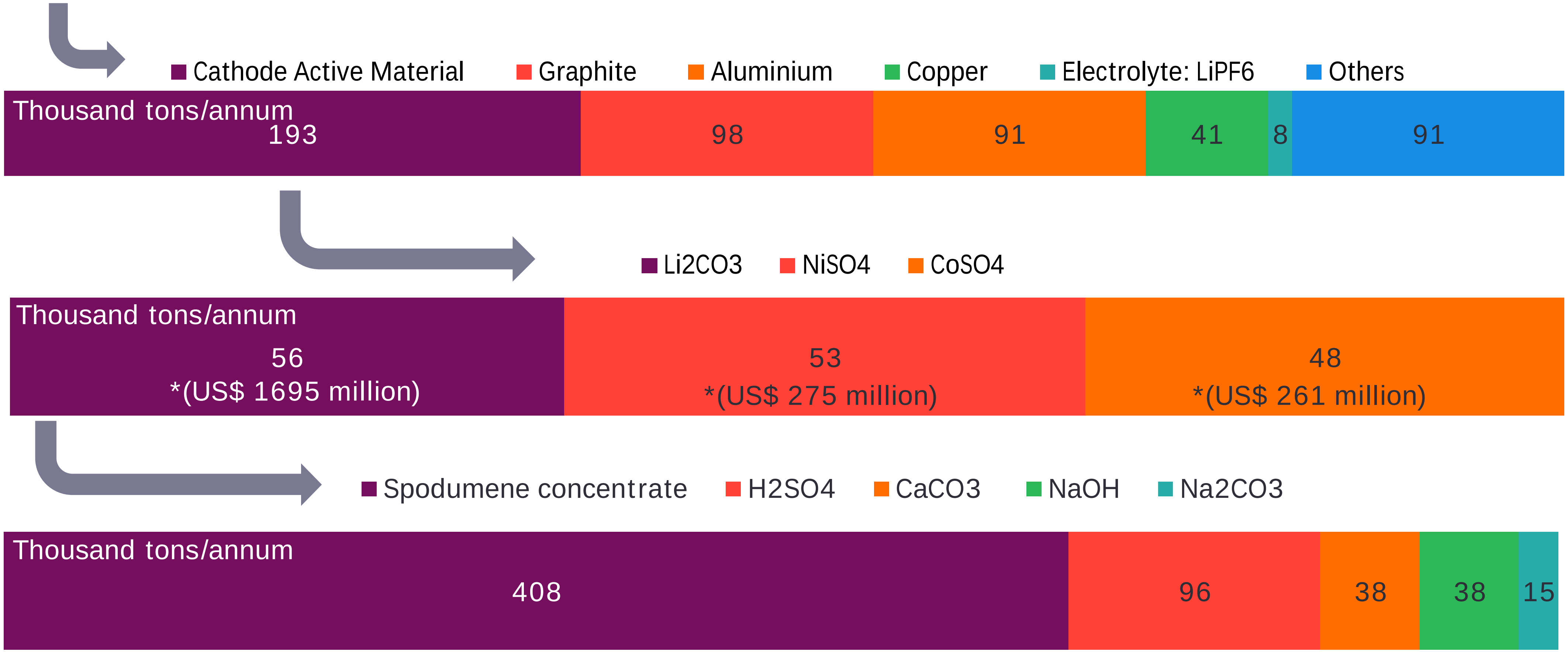
In the final chapter, the report provides key strategies adopted globally for building resilient supply chains of critical minerals, review of government interventions and high-level recommendations (action plan) for different stakeholders involved in the development of critical minerals supply chain, technologies and capital projects.

Overall, the report draws information from various sources in the public domain to analyze the critical minerals supply chain landscape and recommend interventions for supporting domestic value addition in the LIB manufacturing industry by 2030. Some of the key highlights from the report are below:

- India's advance chemistry cell manufacturing industry will need ~193 thousand tons/annum of cathode active material to produce ~100 GWh / annum of batteries by 2030.
- Critical minerals and their active materials used in the production of lithium-ion batteries (LIB) account for approx. 33%-48% of the overall LIB pack cost depending on cathode chemistry and supply chain costs for mining and refining of critical minerals.
- The synthesis of Li-NMC and LFP active materials from critical mineral precursors alone can contribute ~12% domestic value addition in lithium-ion battery (LIB) pack manufacturing.
- Policy should focus on scaling up LIB recycling infrastructure with production linked incentives to complement mining and extraction efforts of critical minerals. This will aid in promoting environmentally sustainable waste management practices, reuse and disposal.
- Promote R&D for earth abundant alternatives to critical minerals used in ACC batteries, support lab to market commercialisation of products, provide start-up incubators and technology industrialisation centres, and facilitate demonstration projects.

Demand for critical minerals and raw materials in the LIB value chain by 2030

Domestic manufacturing capacity of LIBs ~100 GWh/annum by 2030

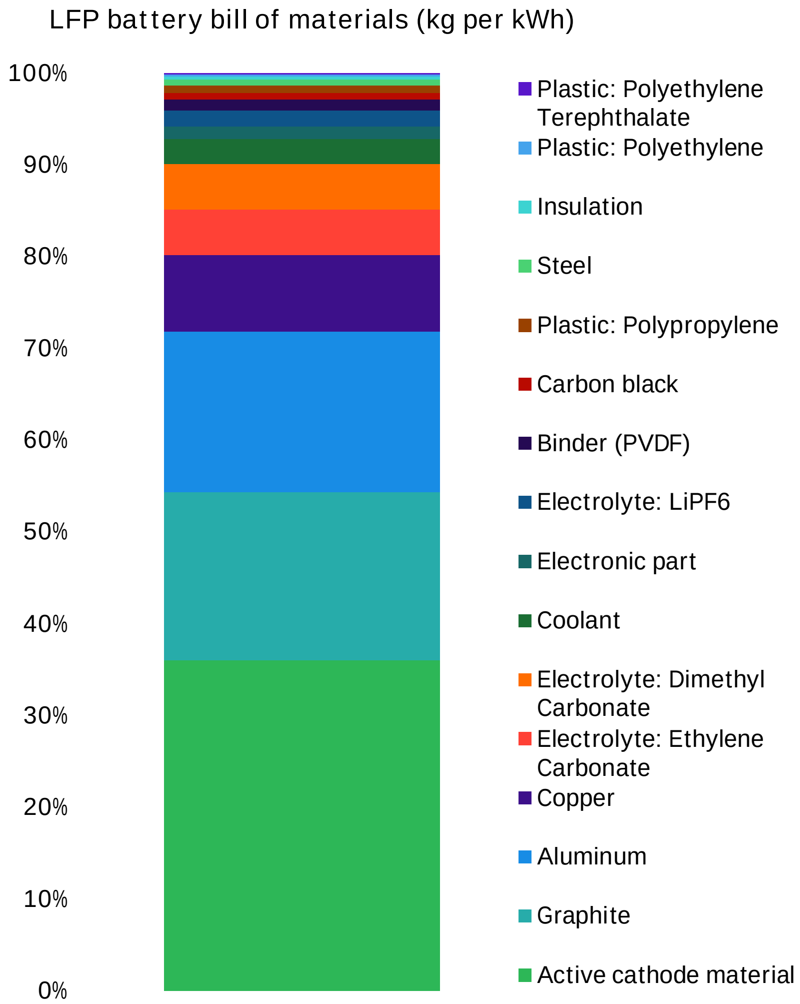


60% LFP
25% NMC
15% LCO

* As per Apr 2023 spot price

88% LiOH
12% Li_2CO_3

Demand for critical minerals and raw materials in the LIB value chain by 2030


LFP battery bill of materials (kg per kWh)

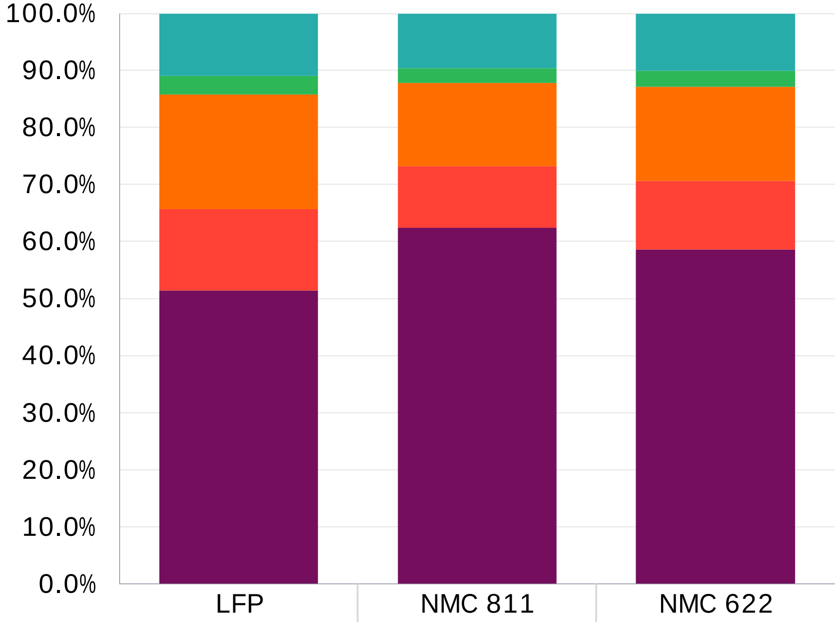
Source: Update of Bill-of-Materials and Cathode Chemistry addition for Lithium-ion Batteries in GREET 2020, Argonne National Laboratory

Item	LMO	NMC111	LFP	NMC532	NMC622	NMC811	NCA
Active cathode material	2.36	1.78	2.06	1.72	1.50	1.27	1.38
Carbon black	0.05	0.04	0.04	0.04	0.03	0.07	0.03
Graphite	0.80	0.90	1.05	0.88	0.89	0.92	0.90
Binder (PVDF)	0.07	0.08	0.06	0.05	0.05	0.09	0.05
Copper	0.44	0.33	0.47	0.31	0.29	0.28	0.26
Aluminum	0.24	0.19	0.26	0.18	0.16	0.16	0.15
Electrolyte: LiPF6	0.08	0.06	0.10	0.06	0.06	0.06	0.05
Electrolyte: Ethylene Carbonate	0.21	0.18	0.29	0.16	0.16	0.16	0.15
Electrolyte: Dimethyl Carbonate	0.21	0.18	0.29	0.16	0.16	0.16	0.15
Plastic: Polypropylene	0.04	0.03	0.05	0.04	0.03	0.03	0.02
Plastic: Polyethylene	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Plastic: Polyethylene Terephthalate	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Subtotal cell	4.50	3.78	4.70	3.61	3.33	3.21	3.17
Module components sans cell (kg)							
Copper	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Aluminum	0.20	0.18	0.23	0.17	0.16	0.16	0.15
Plastic: Polyethylene	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Insulation	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electronic part	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Subtotal : Module components sans cell	0.22	0.20	0.25	0.19	0.19	0.19	0.18
Pack components sans module (kg)							
Copper	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aluminum	0.47	0.44	0.52	0.43	0.42	0.42	0.41
Steel	0.03	0.03	0.04	0.03	0.02	0.03	0.02
Insulation	0.02	0.01	0.02	0.01	0.01	0.01	0.01
Coolant	0.11	0.12	0.15	0.12	0.12	0.12	0.13
Electronic part	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Subtotal : Pack components sans module	0.70	0.67	0.79	0.65	0.64	0.64	0.64
Total pack	5.42	4.65	5.74	4.45	4.15	4.03	3.98

Bill of materials (BOM) in LIB cell to pack assembly (kg per kWh)

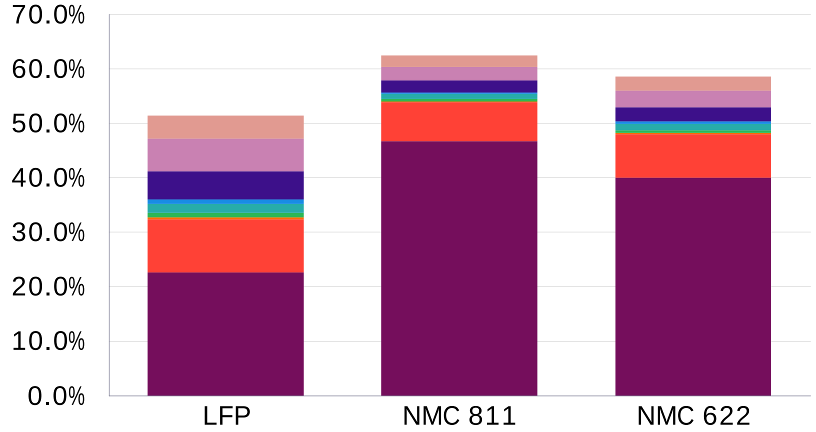
Bill of materials and manufacturing cost breakdown for LIBs

Cost breakdown as % share of LIB pack cost



	LFP	NMC 811	NMC 622
■ Total cost of profits and warranty	10.9%	9.7%	10.1%
■ Total cost of BMS	3.3%	2.6%	2.8%
■ Total cost of manufacturing	20.2%	14.6%	16.5%
■ Total cost of purchased items	14.3%	10.7%	12.0%
■ Total cost of materials	51.4%	62.4%	58.6%

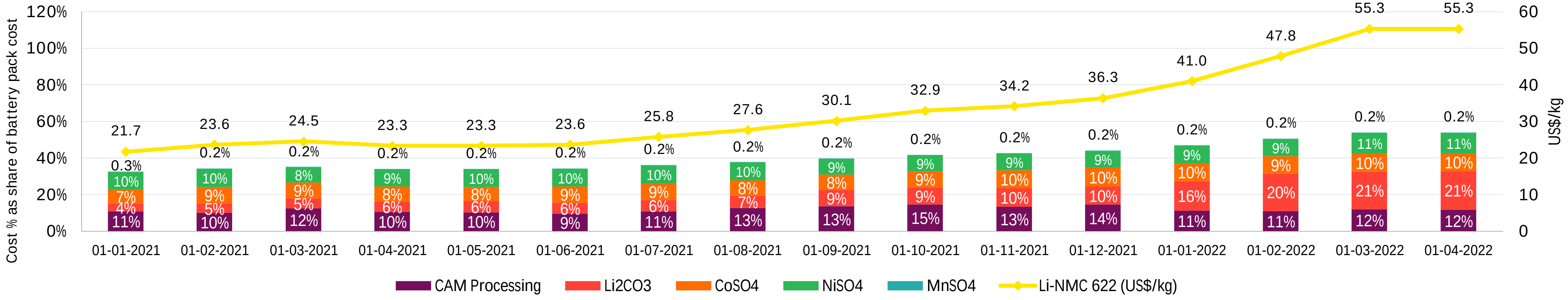
Material cost break down as % share of LIB pack cost



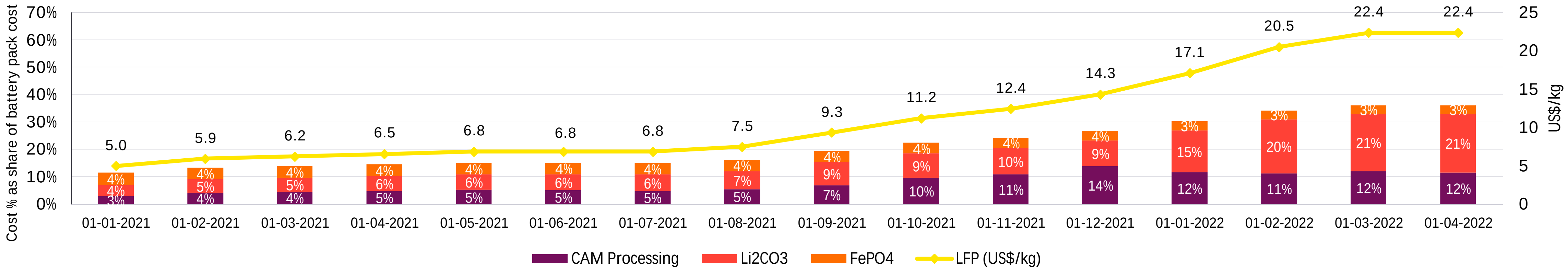
	LFP	NMC 811	NMC 622
■ Additives	0.0%	0.0%	0.0%
■ Electrolyte	4.2%	2.2%	2.6%
■ Separators	6.1%	2.5%	3.1%
■ Negative current collector	5.1%	2.1%	2.6%
■ Positive current collector	0.8%	0.3%	0.4%
■ Solvents	1.7%	0.9%	1.1%
■ Binders	0.8%	0.5%	0.6%
■ Carbon additive	0.3%	0.2%	0.2%
■ Negative active material	9.8%	7.1%	7.9%
■ Positive active material	22.6%	46.7%	40.1%

Value addition from cathode active materials in the production of LIBs

Cost breakdown of cathode active material as a % share of NMC-622 LIB pack cost



Cost breakdown of cathode active material as a % share of LFP LIB pack cost



2030 Action plan for building resilience in critical battery mineral supply chains

Strategic intervention	Action Plan
Domestic exploration, mining and refining of critical mineral resources	• National stockpiling of refined mineral precursors used in LIB electrodes • Incentives for critical battery mineral exploration, mining and extraction through appropriate royalty and tax regimes • PLI for setting up critical mineral processing / refining units, especially for Li_2CO_3 / LiOH, $NiSO_4$, $CoSO_4$ and Spherical graphite • Production linked incentives for extraction of critical minerals through recycling LIBs
Overseas exploration and mining of critical mineral resources	• Strengthen Indian missions in critical mineral bearing foreign countries to facilitate due diligence of greenfield / brownfield mining assets, acquisition and investment by Indian companies • Strengthen KABIL to plan and undertake joint exploration, mining activities in critical mineral bearing foreign countries
Establish supply chain linkages with friendly foreign countries	• "G20 Critical Minerals Security Partnership" should focus on building resilient supply chain of critical battery minerals, including stockpiles in different member countries as per comparative advantages in extraction and processing • Critical Battery Minerals Supply Chain should be prioritized as a key pillar of Indo-Pacific economic framework and a key factor in diplomatic outreach with mineral bearing foreign countries

R&D to develop recycling, extraction technologies and find earth abundant alternatives to critical battery minerals	• Formulate national R&D grand challenge for:
	  • developing high performance LIB electrodes made from earth abundant alternatives
	  • direct lithium extraction technologies from seawater that can selectively separate lithium from sea water using physical or chemical processes

CONTENTS

Acronyms

ACU	Acid Purification Unit
ADB	Asian Development Bank
Al	Aluminum
AMD	Atomic Minerals Directorate
AP	Andhra Pradesh
ARCI	International Advanced Research Centre for Powder Metallurgy and New Materials
BatPaC	Battery Performance and Cost
BMS	Battery Management System
Ca	Calcium
$CaCO_3$	Calcium carbonate
CAGR	Compound Annual Growth Rate
CAM	Cathode active material
CaO	Calcium oxide
CAPEX	Capital Expenditure
CCD	Counter Current Decanation
CERCI	Central Electrochemical Research Institute
Cl_2	Chlorine
CMSP	Critical Battery Minerals Supply Chain
Co	Cobalt
$Co(OH)_2$	Cobaltous Hydroxide
CO_2 eq.	Carbon dioxide equivalent
Co_3O_4	Cobalt(II, III) oxide
$CoCO_3$	Cobalt carbonate
CoOOH	Cobaltic Oxyhydroxide
Co-PGE	Cobalt–Platinum–Group Element

$CoSO_4$	Cobalt sulfate
$CoSO_4.7H_2O$	Cobalt sulfate heptahydrate
CSIR	Council of Scientific & Industrial Research
Cu	Copper
DAE	Department of Atomic Energy
DEA	Department of Economic Affairs
DIPP	Department of Industrial Policy and Promotion
DMG	Department of Mines and Geology
DMIC	Delhi Mumbai Industrial Corridor
DMT	Dimethyl Terephthalate
DPIIT	Department for Promotion of Industry and Internal Trade
DRC	Democratic Republic of Congo
DST	Department Of Science & Technology
EMD	Electrolytic Manganese Dioxide
EMEW	Electro metal Electro winning
EPCM	Engineering, Procurement and Construction Management
ETP	Effluent Treatment Plant
EVs	Electric Vehicles
EW	Electrowinning
EY	Ernst & Young
FC	Fixed Carbon
FCI	Fixed Capital investment
Fe	Iron
Fe	Iron
$FePO_4$	Ferric phosphate

FSP	Field Season Program
g	grams
G2G	Government to Government
GHG	Greenhouse Gases
GSI	Geological Survey of India
GWh	Gigawatt hours
GWP	Global Warming Potential
H_2SO_4	Sulfuric acid
HCL	Hindustan Copper Limited
HCl	Hydrochloric acid
HPAL	High Pressure Acid Leaching
HPCL	Hindustan Petroleum Corporation Ltd.
HRRL	HPCL Rajasthan Refinery Limited
HS Code	Harmonized System Code
ICC	Indian Copper Complex
IEM	Industrial Entrepreneur Memorandum
IFA	Investor Facilitation Agency
IMMT	Institute of Minerals and Materials Technology
INR	Indian Rupee
IOCL	Indian Oil Corporation Ltd.
ISRO	Indian Space Research Organisation
ITC	Indian Trade Clarification
J&K	Jammu & Kashmir
JNPT	Jawaharlal Nehru Port Trust
JV	Joint Venture
KABIL	Khanij Bidesh India Ltd.
kg	Kilograms
Kt	Kilo tons

Acronyms

ktPA	Kilo tons Per Annum
kWh	Kilowatt hours
LCE	Lithium carbonate equivalent
LCO	Lithium Cobalt Oxide
LFP	Lithium iron phosphate
Li	Lithium
Li_2CO_3	Lithium carbonate
Li_2O	Lithium oxide
LIB	Lithium-ion battery
Li-NMC	Lithium – Nickel Manganese Cobalt
LiOH	Lithium hydroxide
$LiOH.H_20$	Lithium hydroxide monohydrate
$LiPF_6$	Lithium hexafluorophosphate
LME	London Metal Exchange
LMO	Lithium Manganese Oxide
LOM	Life of Mine
m^3	Cubic meter
MECL	Mineral Exploration and Consultancy Limited
MEMC	Mineral Evidence and Mineral Content
Mg	Magnesium
mg/L	Milligrams per liter
MgO	Magnesium oxide
MJ	Mega Joules
MM(D&R)	Mines and Minerals (Development and Regulation)
MMBtu	Metric Million British Thermal Unit
MMTPA	Million Metric Tons Per Annum

Mn	Manganese
MnSO4	Manganese sulfate
MOIL	Manganese Ore (India) Limited
MSME	Micro, Small and Medium Enterprises
MTPA	Metric Tons Per Annum
Na_2CO_3	Sodium carbonate / Soda ash
$Na_2S_2O_5$	Sodium metabisulfite
Na_2SO_4	Sodium Sulfate
NACL	Nagarjuna Oil Corporation Ltd.
NALCO	National Aluminium Company Limited
NaOH	Sodium hydroxide / Caustic soda
NCA	Nickel Cobalt Aluminum oxide
NH_4	Ammonium
NH_4HCO_3	Ammonium bicarbonate
Ni	Nickel
$NiSO_4$	Nickel sulfate
NITI Aayog	National Institution for Transforming India
NMC	Nickel Manganese Cobalt
NMDC	National Mineral Development Corporation
OEM	Original Equipment Manufacturer
OPAL	ONGC Petro Additions Limited
OPEX	Operational Expenditure
P	Phosphorus
P-204	Di (2-ethylhexyl) phosphate
Pb	Lead

PCPIR	Petroleum, Chemicals and Petrochemicals Investment Region
PLI	Production Linked Incentives
PM	Particulate Matter
PM 10	Particulate Matter 10
PM 2.5	Particulate Matter 2.5
ppm	Parts per million
PVDF	Polyvinylidene Fluoride
R&D	Research and Development
RIICO	Rajasthan State Industrial Development and Investment Corporation Limited
ROI	Return on Investment
S	Sulfur
SEI	Solid Electrolyte Interphase
SO_2	Sulfur Dioxide
t	ton
tpa	tons per annum
TPA	Terephthalic Acid
tpd	tons per day
tpy	tons per year
UNFC	United Nations Framework Classification
US	United States
US$	United State Dollar
UT	Union Territory
VCIC	Vizag-Chennai Industrial Corridor
Zn	Zinc

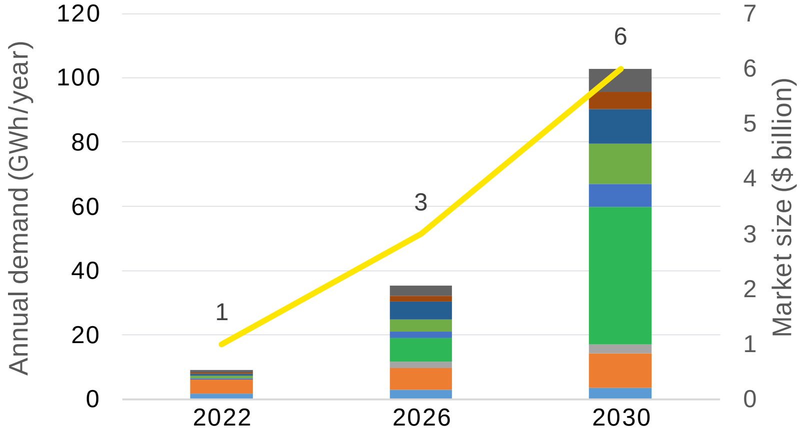
01

Lithium-ion battery: bill of materials and demand outlook for critical minerals

Indian battery demand outlook

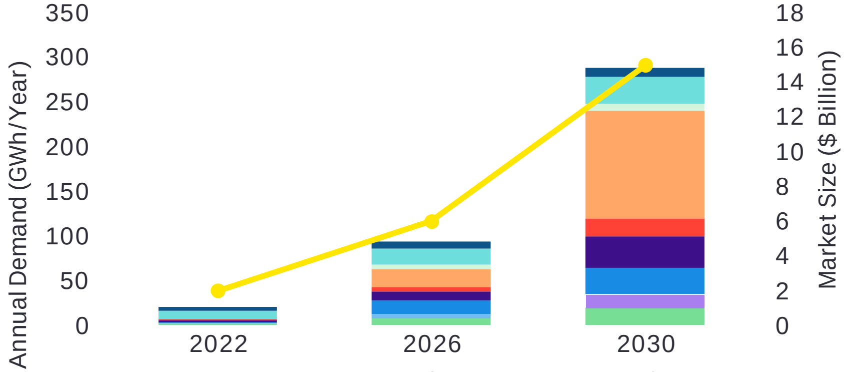
There is a need for the battery manufacturing industry to secure its supply chain and boost domestic value addition

India battery demand outlook (conservative scenario)



	2022	2026	2030
Passenger EVs	1	3	7
Commercial EVs	0	2	5
E 2-wheeler/3-wheeler	0	6	11
E-buses	1	4	12
Freight	0	2	7
Stationary storage (grid scale)	0	8	43
Behind the meter (Residential + Commercial)	0	2	3
Consumer electronics	4	7	11
Rail + Defense	2	3	4
Market size	1	3	6

India battery demand outlook (accelerated scenario)



	2022	2026	2030
Rail + Defense	4	8	10
Consumer Electronics	10	18	30
Behind-the meter (Res + Comm)	0	5	8
Stationary Storage (Grid-scale)	0	20	120
Freight	1	5	20
E-buses	2	10	35
E 2-wheeler/3-wheeler	1	15	30
Commercial Evs	1	5	15
Passenger Evs	2	8	20
Market Size	2	6	15

Source: RMI and NITI Aayog 2022

The manufacturing value chain of lithium-ion battery

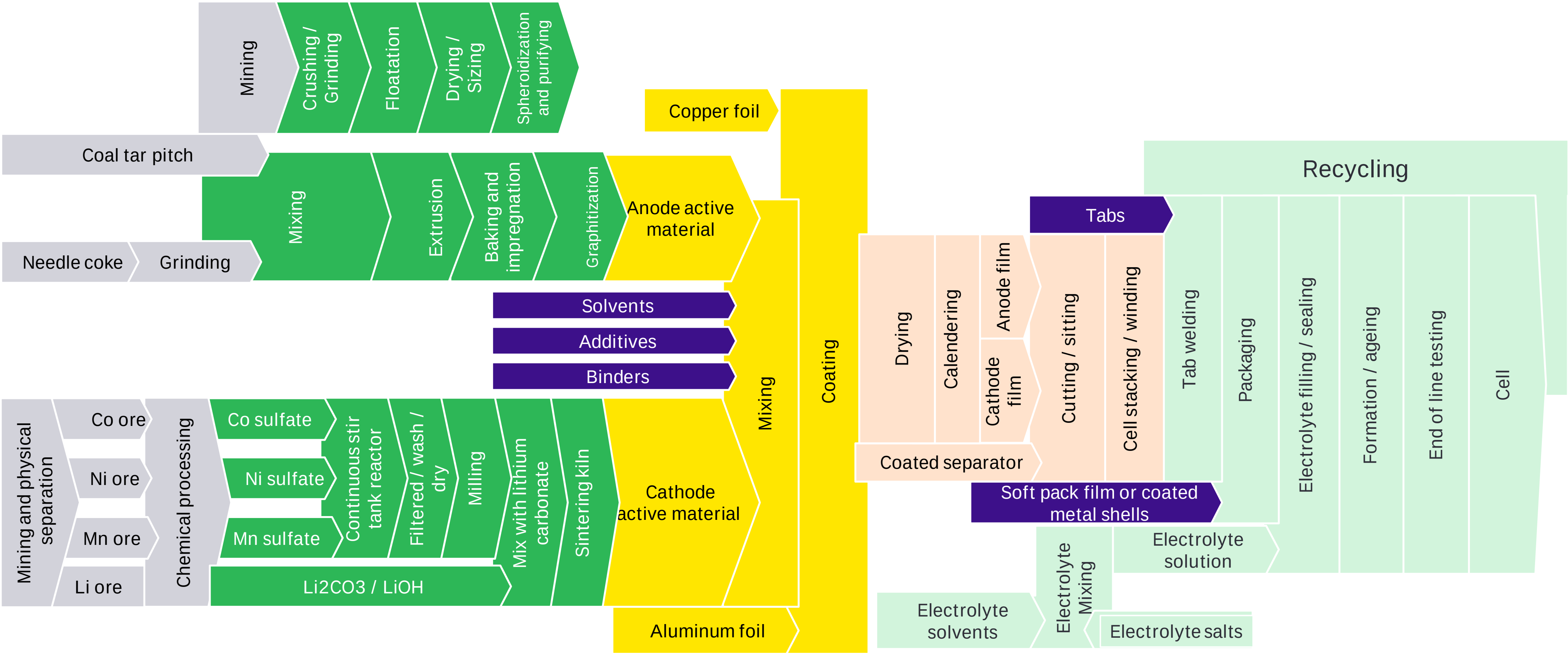
Mining
Extraction of raw materials, such as Li, Co, Ni, Mn and graphite

Chemical processing
Conversion of raw materials into intermediate compounds

Active material production
Manufacturing of electrode materials, such as NMC, LFP, etc.

Cell production
Integration of electrodes, electrolytes, and separators into a sealed unit

Recycling
Reclamation of valuable materials from used batteries



Mining → Crushing / Grinding → Floatation → Drying / Sizing → Spheroidization and purifying

Coal tar pitch

Needle coke → Grinding

Mixing → Extrusion → Baking and impregnation → Graphitization → Anode active material

Copper foil

Solvents

Additives

Binders

Mining and physical separation: Co ore, Ni ore, Mn ore, Li ore

Chemical processing: Co sulfate, Ni sulfate, Mn sulfate, Li2CO3 / LiOH

Continuous stir tank reactor → Filtered / wash / dry → Milling → Mix with lithium carbonate → Sintering kiln → Cathode active material

Aluminum foil

Mixing

Coating

Drying → Calendering → Anode film / Cathode film → Cutting / sitting → Cell stacking / winding

Coated separator

Tabs

Soft pack film or coated metal shells

Electrolyte solvents

Electrolyte Mixing

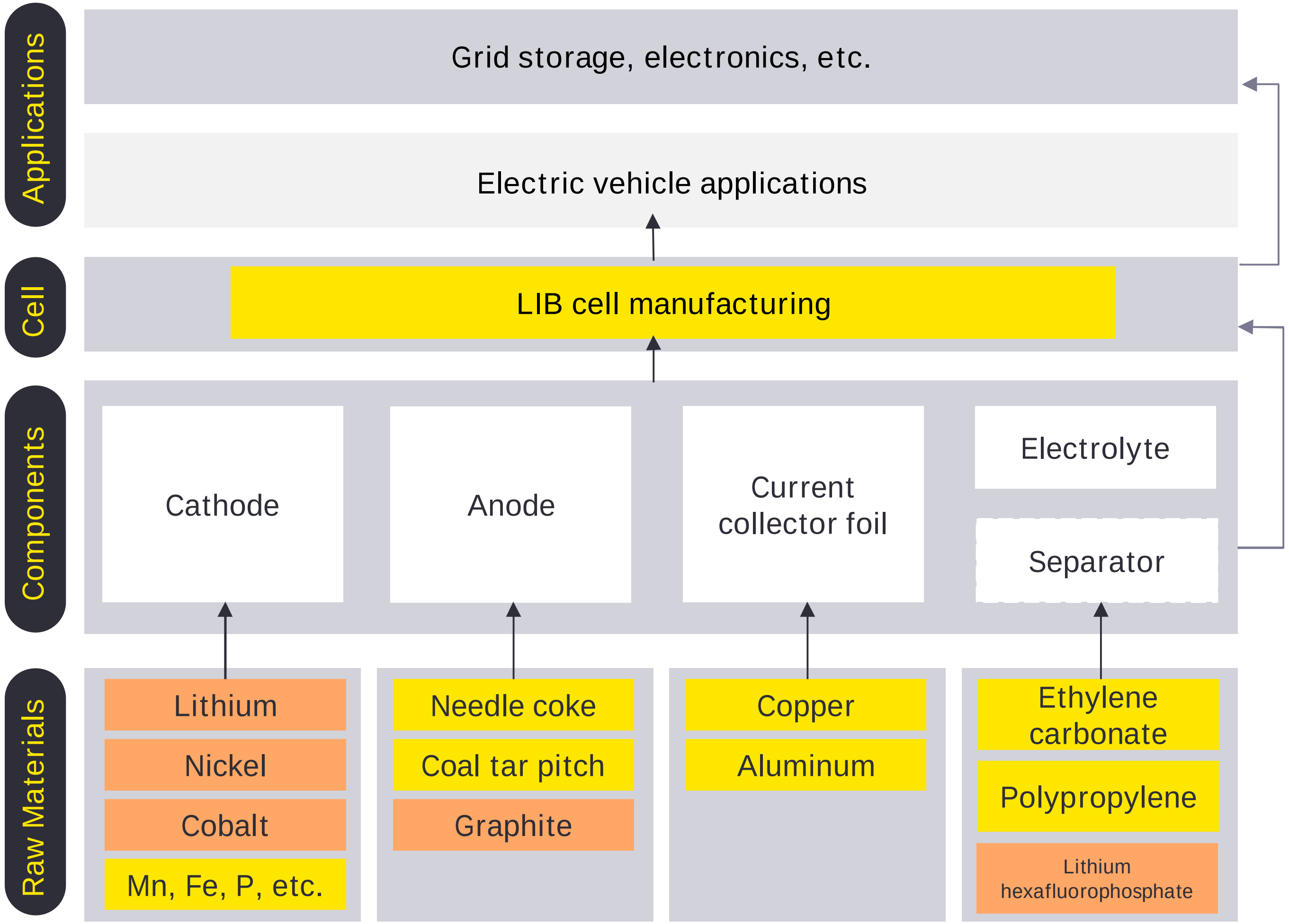
Electrolyte salts

Electrolyte solution

Tab welding → Packaging → Electrolyte filling / sealing → Formation / ageing → End of line testing → Cell

Recycling

Key components and materials for manufacturing lithium-ion batteries (LIBs)

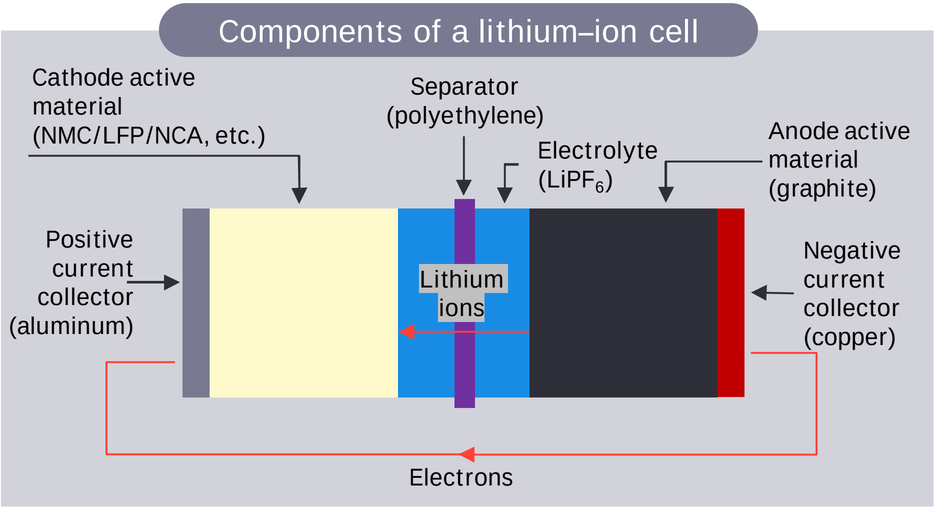


🟧 Supply chain bottlenecks

🟨 Sizeable domestic supply chain exists

- Commercially available LIB cell cathode and anode production will need active materials, such as NMC, LFP, NCA, LCO, LMO, spherical graphite, for different types of electrode chemistry. Active material synthesis will require battery grade processed chemical precursors of critical mineral commodities (e.g., lithium carbonate, nickel and cobalt sulfates).
- Moreover, Li-ion cells use polyolefin as ion exchange separators. This material has excellent mechanical properties, decent chemical stability and low-cost. Polyolefins are a class of polymer derived from olefins (alkenes) through the polymerization of ethylene, which is sourced from petrochemicals. Polyolefins can be manufactured using polyethylene, polypropylene, or a combination of both materials in the form of laminates. The separator must be permeable with pore size ranging from 30nm to 100nm. The recommended porosity is 30% to 50%.

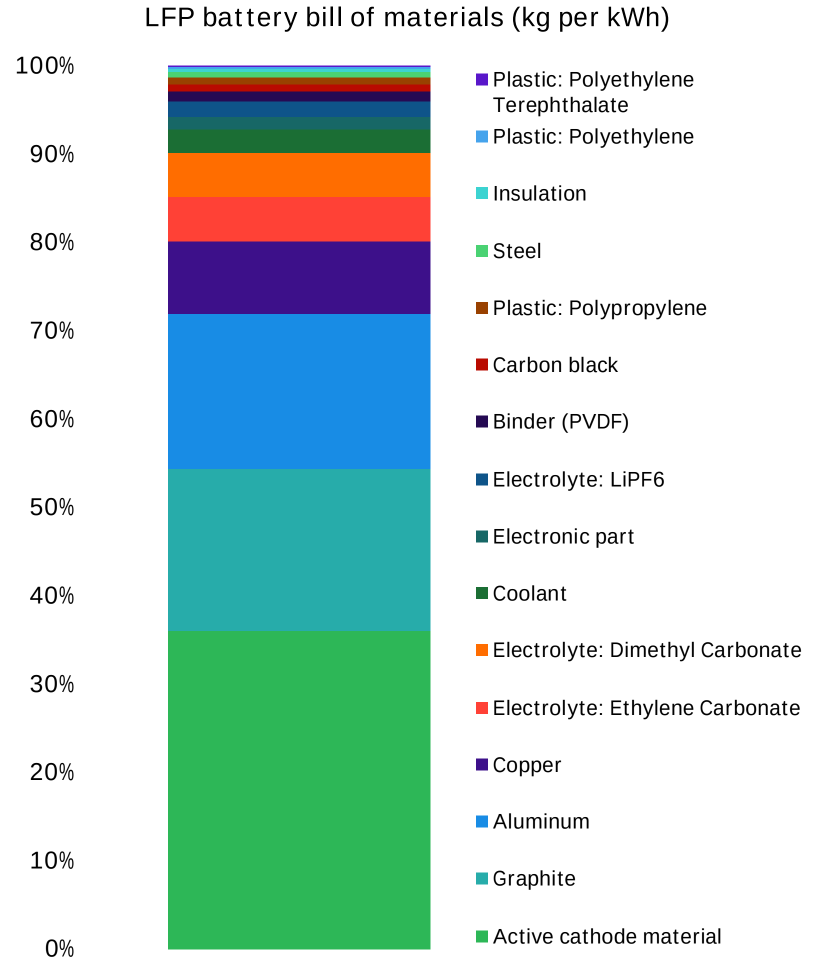
Components of a lithium–ion cell



Source: how-can-india-scale-lithium-ion-battery-manufacturing-sector-and-supply-chain.pdf (ceew.in)

Lithium-ion battery (LIB) manufacturing Bill of Materials

Bill of materials reveals that cells account for ~80% of the total weight of the battery pack, with NCA exhibiting the highest gravimetric energy density



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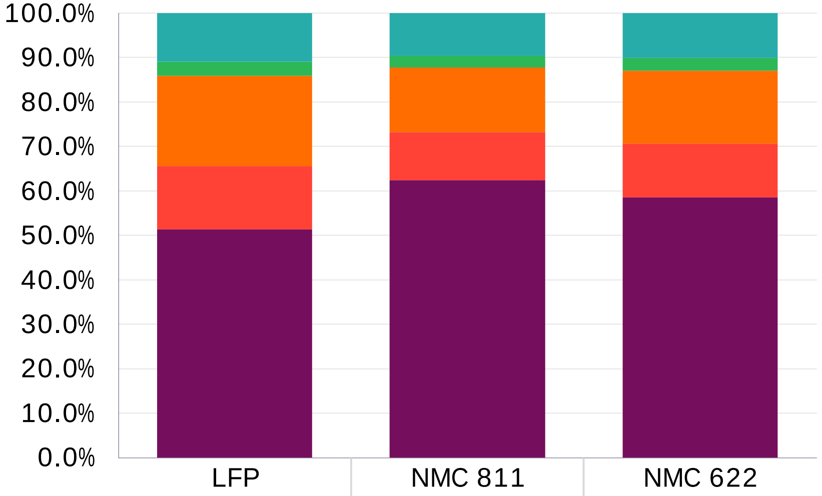
Plastic: Polyethylene	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Insulation	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electronic part	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Subtotal : Module components sans cell	0.22	0.20	0.25	0.19	0.19	0.19	0.18
Pack components sans module (kg)							
Copper	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aluminum	0.47	0.44	0.52	0.43	0.42	0.42	0.41
Steel	0.03	0.03	0.04	0.03	0.02	0.03	0.02
Insulation	0.02	0.01	0.02	0.01	0.01	0.01	0.01
Coolant	0.11	0.12	0.15	0.12	0.12	0.12	0.13
Electronic part	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Subtotal : Pack components sans module	0.70	0.67	0.79	0.65	0.64	0.64	0.64
Total pack	5.42	4.65	5.74	4.45	4.15	4.03	3.98

Source: Update of Bill-of-Materials and Cathode Chemistry addition for Lithium-ion Batteries in GREET 2020, Argonne National Laboratory

Bill of materials (BOM) in LIB cell to pack assembly (kg per kWh)

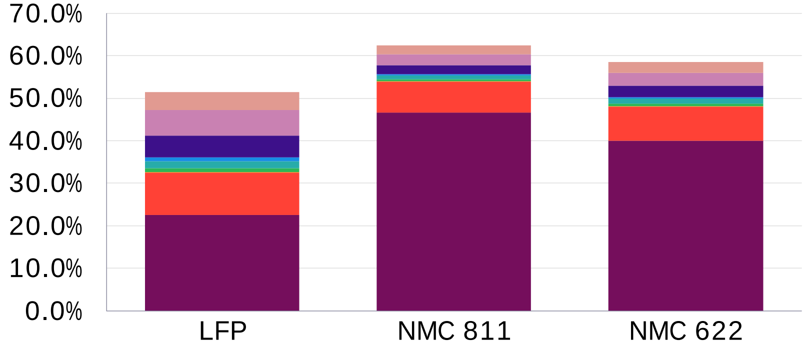
Cost breakdown of manufacturing LIBs indicates active materials synthesized from critical mineral commodities and their chemical precursors can contribute up to ~55% of overall cost

Cost breakdown as % share of LIB pack cost



	LFP	NMC 811	NMC 622
🟦 Total cost of profits and warranty	10.9%	9.7%	10.1%
🟩 Total cost of BMS	3.3%	2.6%	2.8%
🟧 Total cost of manufacturing	20.2%	14.6%	16.5%
🟥 Total cost of purchased items	14.3%	10.7%	12.0%
🟪 Total cost of materials	51.4%	62.4%	58.6%

Material cost break down as % share of LIB pack cost



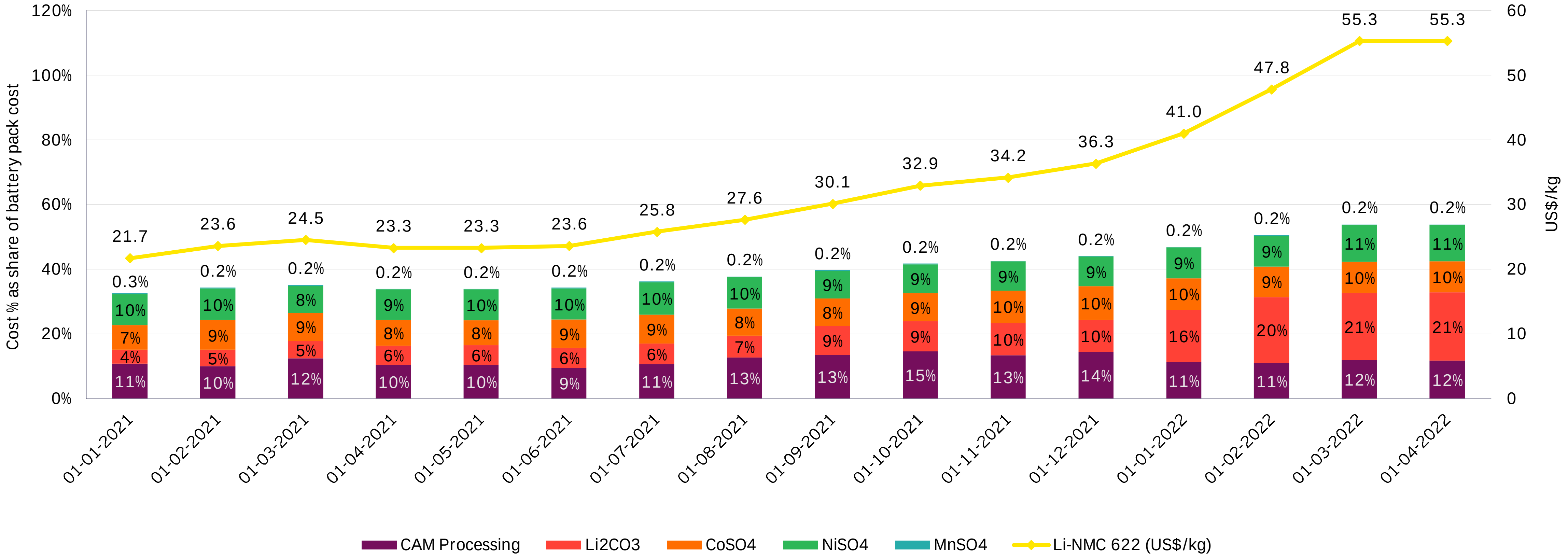
	LFP	NMC 811	NMC 622
🟨 Additives	0.0%	0.0%	0.0%
🟥 Electrolyte	4.2%	2.2%	2.6%
🟪 Separators	6.1%	2.5%	3.1%
🟪 Negative current collector	5.1%	2.1%	2.6%
🟦 Positive current collector	0.8%	0.3%	0.4%
🟦 Solvents	1.7%	0.9%	1.1%
🟩 Binders	0.8%	0.5%	0.6%
🟧 Carbon additive	0.3%	0.2%	0.2%
🟥 Negative active material	9.8%	7.1%	7.9%
🟪 Positive active material	22.6%	46.7%	40.1%

Sources: EY analysis based on BatPaCV5.0 by UChicago Argonne, LLC

Note: Cost breakdown is estimated by over riding default value for positive active material cost in BatPaCV5.0 @ current market prices, (i.e. LFP cathode powder – US$ 11.37/kg; NMC811 cathode powder – US$ 44.46/kg; NMC622 cathode powder – US$ 30.61/kg, April 2023 prices). Ternary Precursor and Material prices | New Energy | SMM - China Metal Market

Synthesizing Li-NMC active material and the critical mineral precursors can have up to ~40% value addition in LIB pack manufacturing

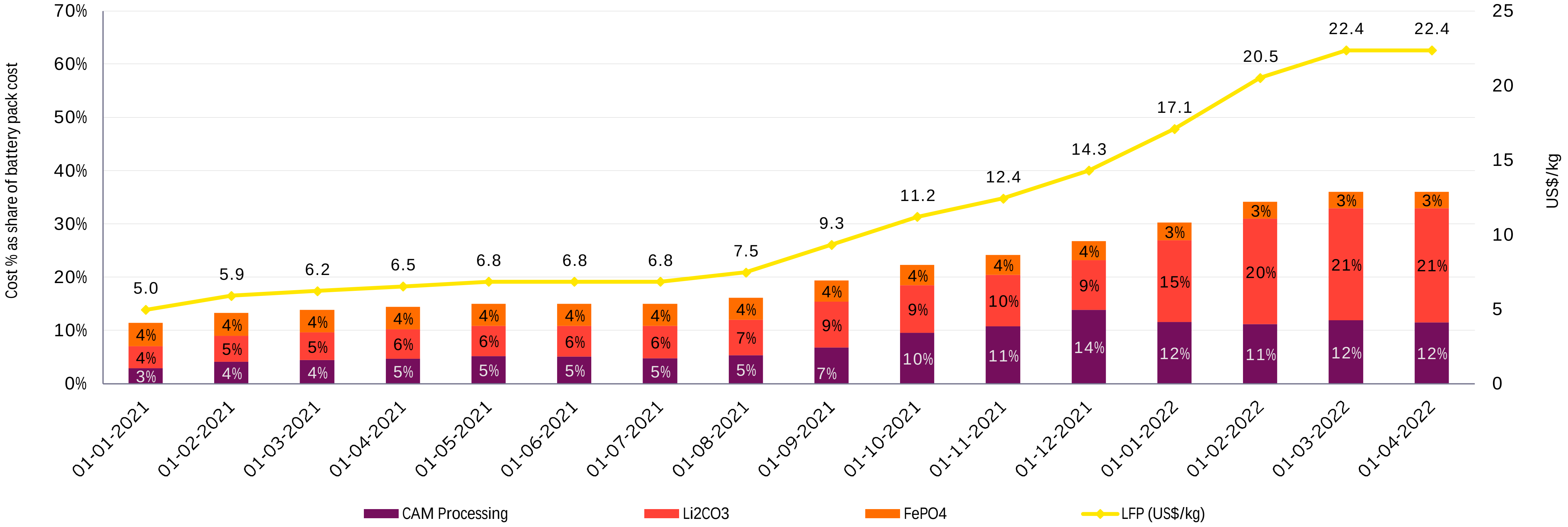
Cost breakdown of cathode active material as a % share of NMC-622 LIB pack cost



Source: EY Analysis based on market (spot) prices for active materials and their critical mineral constituents (battery grade chemical precursors) from the period of Jan 2021 – April 2022.
Note: The prices considered for Li-NMC 622 powder is taken from "https://source.benchmarkminerals.com/article/cathode-prices-fall-for-first-time-since-may-on-weaker-demand", prices for Li_2CO_3, Cobalt and Nickel is taken from internal EY data and for $MnSO_4$ a constant price of US$ 1.5/kg is considered for the period of Jan 2021 – April 2022.

Synthesizing LFP active material and the critical mineral precursors can have up to ~23% value addition in LIB pack manufacturing

Cost breakdown of cathode active material as a % share of LFP LIB pack cost

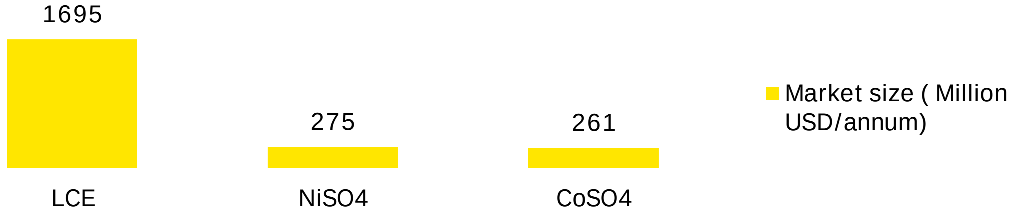


Source: EY Analysis based on market (spot) prices for active materials and their critical mineral constituents (battery grade chemical precursors) from the period of Jan 2021 – April 2022.
Note: The prices considered for LFP powder is taken from "https://source.benchmarkminerals.com/article/cathode-prices-fall-for-first-time-since-may-on-weaker-demand", prices for Li2CO3 is taken from internal EY data and for FePO4 a constant price of US$ 2/kg is considered for the period of Jan 2021 – April 2022.

Demand outlook for critical materials required to manufacture 100 GWh/annum LIBs by 2030

- India's LIB cell manufacturing industry will need ~193 thousand tons/annum of cathode active material, ~98 thousand tons /annum of anode active material, 91 thousand tons /annum of aluminum and 41 thousand tons of copper and 8 thousand tons/annum of LiPF6 electrolyte material to produce ~100 GWh / annum of batteries by 2030.
- The demand for chemical precursors of metals such Li, Ni and Co will depend on the cathode chemistry demand for various applications. LFP could be the dominant cathode chemistry for manufacturing LIBs serving electric bus deployment, stationary grid storage and behind the meter storage applications. The share of LFP in the demand for active cathode material could be ~60%.
- Similarly, NMC is another dominant cathode chemistry for manufacturing LIBs catering to passenger EVs, commercial EVs and two-wheeler EV markets. The share of NMC in the demand for active cathode material could be ~25%. LCO is another cathode chemistry used in consumer electronics. The share of LCO in the overall demand for active cathode material could be ~15%.

Market size (@April 2023 spot prices) of battery grade specialty metals for domestic manufacturing by 2030 (US$/annum)



Critical materials	Demand to manufacture 100 GWh / annum LIBs (Thousand tons/annum)
Cathode active material	193
Graphite	98
Aluminum	91
Copper	41
Electrolyte: $LiPF_6$	8

Chemical precursors	Demand to manufacture ~193 thousand ton/annum active cathode material (Thousand tons/annum)
Li_2CO_3	56
$NiSO_4$	53
$CoSO_4$	48

Source: 1. Nickel sulfate vs metal: Is the market shifting towards new pricing mechanisms? | S&P Global Commodity Insights (spglobal.com)
2. Green Metals Battery Metals Watch The end of the beginning (goldmansachs.com)

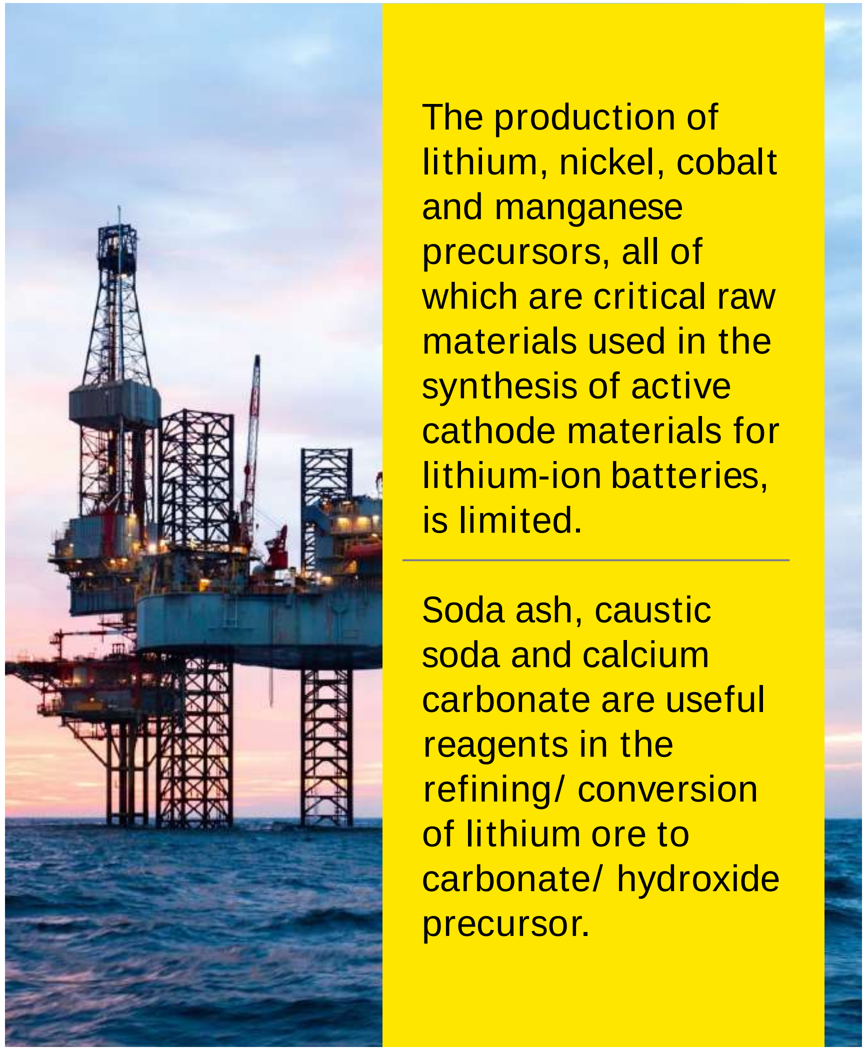
02

Status quo analysis of critical mineral supply chain relevant for battery manufacturing in India

Capacity and production of non-ferrous metals and inorganic chemicals in India

Mineral-based product	Unit	Annual installed capacity	Production	
			2018-19	2019-20
Nou-ferrous Metals				
Aluminum	million tons	4.1	3.7	3.6
Copper (Cathode)	thousand tons	1,001.5	454.0	408.0
Lead (primary)	thousand tons	201.0	198.0	132.0
Zinc Ingots	thousand tons	881.0	696.0	516.0
Silver	tons	600.0	751.0	442.0
Chemicals				
Aluminum fluoride	thousand tons	25.6	5.7	5.1
Caustic soda	thousand tons	3,700.0	2,925.0	3,137.0
Calcium carbide	thousand tons	112.0	83.2	81.3
Soda ash	thousand tons	3,614.0	3,048.0	3,069.0
Titanium dioxide pigment	thousand tons	82.5	57.1	49.5
Red phosphorus	thousand tons	1.7	1.0	1.0

Source: Indian Minerals Yearbook 2020, (Part- I: General Reviews); 59th Edition, MINERAL-BASED INDUSTRIES, INDIAN BUREAU OF MINES, September 2022



The production of lithium, nickel, cobalt and manganese precursors, all of which are critical raw materials used in the synthesis of active cathode materials for lithium-ion batteries, is limited.

Soda ash, caustic soda and calcium carbonate are useful reagents in the refining/ conversion of lithium ore to carbonate/ hydroxide precursor.

Capacity and production of major inorganic chemicals in India

Numbers are in thousand metric tons

Major Groups / Products	Installed Capacity			Production								CAGR (%)	Capacity Utilization in 2020-21
	2018-19	2019-20	2020-21	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21		
Alkali Chemicals													
Soda Ash	3,489.0	3,614.0	3,614.0	2,392.2	2,462.0	2,583.0	2,613.4	2,989.6	3,048.2	3,069.4	2,638.1	1.4	73.0
Caustic Soda	3,397.3	3,700.3	3,898.2	2,391.7	2,442.9	2,504.0	2,594.5	2,742.3	2,925.4	3,136.9	2,964.1	3.1	76.0
Liquid Chlorine	2,535.3	2,774.7	2,961.2	1,697.3	1,720.1	1,714.8	1,800.7	1,899.4	2,069.1	2,250.4	2,174.3	3.6	73.4
Total	9,421.6	10,089.1	10,473.4	6,481.2	6,625.0	6,801.8	7,008.6	7,631.3	8,042.7	8,456.8	7,776.5	2.6	74.3
Inorganic Chemicals													
Aluminum Fluoride	25.6	25.6	25.6	5.4	6.7	9.5	8.1	7.5	5.7	5.1	3.7	-5.3	14.5
Calcium Carbide	112.0	112.0	112.0	78.8	87.2	83.5	85.0	87.3	83.2	81.3	86.8	1.4	77.5
Carbon Black	696.0	696.0	696.0	406.4	444.4	469.6	535.3	530.4	546.4	500.2	384.8	-0.8	55.3
Potassium Chlorate	4.6	28.6	28.6	0.7	0.5	0.4	0.0	0.4	0.7	16.2	17.1	58.6	59.7
Sodium Chlorate	-	-	22.3	-	-	-	-	-	-	-	17.9		80.3
Titanium Dioxide	82.5	82.5	82.5	52.8	47.9	58.5	58.5	57.8	57.1	49.5	51.2	-0.4	62.1
Red Phosphorus	1.7	1.7	1.7	0.8	0.9	0.8	0.8	0.9	1.0	1.0	1.1	5.1	63.5
Hydrogen Peroxide	145.9	218.6	218.6	128.4	119.8	153.1	148.9	157.0	156.5	122.8	139.9	1.2	64.0
Potassium Iodate	-	1.2	1.2	-	-	-	-	-	-	0.6	0.5		45.2
Calcium Carbonate	231.6	371.6	371.6	233.1	236.9	226.1	216.3	217.3	213.3	286.8	274.8	2.4	74.0
Total	1,299.8	1,537.8	1,560.1	906.3	944.2	1,001.5	1,052.9	1,058.5	1,063.8	1,063.5	977.8	1.1	62.7

Source: CHEMICAL AND PETROCHEMICAL STATISTICS AT A GLANCE - 2021, Ministry of Chemicals and Fertilizers, Department of Chemicals and Petrochemicals, Statistics and Monitoring Division

Imports of major inorganic chemicals in India

Quantity in metric tons and Value in Lakhs INR

Product	2013-14		2014-15		2015-16		2016-17		2017-18		2018-19		2019-20		2020-21	
	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
Alkali Chemicals																
Soda Ash	569,420	79,817	725,517	112,616	633,263	101,707	695,307	102,490	772,622	111,757	840,591	144,900	847,704	152,515	719,731	114,804
Caustic Soda	304,653	73,038	407,981	93,584	484,133	116,303	425,795	112,391	421,298	153,382	208,267	79,927	309,345	87,982	248,057	55,495
Liquid Chlorine	86	112	648	274	482	189	35	170	58	208	266	696	81	255	39	200
Total	874,159	152,967	1,134,146	206,474	1,117,878	218,199	1,121,137	215,051	1,193,978	265,347	1,049,124	225,523	1,157,130	240,752	967,827	170,499
Inorganic Chemicals																
Aluminum Fluoride	24,542	17,383	30,120	20,259	27,258	18,102	46,564	26,437	49,758	29,075	62,374	56,075	40,362	37,910	61,224	48,059
Calcium Carbide	64,239	26,743	78,332	31,525	61,935	25,429	55,692	23,652	55,651	23,941	45,321	21,554	31,218	14,507	32,666	17,749
Carbon Black	145,939	112,823	139,468	108,915	124,059	83,401	128,740	82,424	186,224	143,618	278,531	249,368	197,491	153,367	190,469	127,583
Potassium Chlorate	7,040	4,357	6,147	3,856	3,160	2,026	100	61	29	22	128	272	55	119	909	884
Sodium Chlorate	28,083	11,570	21,818	9,085	17,298	6,400	7,447	2,907	8,822	3,041	14,240	5,884	24,082	11,254	11,589	5,118
Titanium Dioxide	16,875	29,196	17,574	28,243	16,421	25,709	13,901	22,943	13,701	24,771	14,546	28,686	16,416	30,825	13,389	25,107
Red Phosphorus	266	750	36	98	-	-	-	1	-	3	14	51	18	57	4	18
Hydrogen Peroxide	62,527	16,443	56,276	14,311	44,084	11,211	57,068	15,910	68,474	19,305	84,261	36,931	52,727	15,858	22,355	8,150
Calcium Carbonate	524,395	46,575	562,198	51,581	715,606	65,090	700,559	60,902	846,195	64,587	1,080,252	86,942	1,169,457	90,705	855,385	69,433
Total	873,906	265,840	911,969	267,873	1,009,821	237,368	1,010,071	235,237	1,228,854	308,363	1,579,667	485,763	1,531,826	354,602	1,187,990	302,101

Source: CHEMICAL AND PETROCHEMICAL STATISTICS AT A GLANCE - 2021, Ministry of Chemicals and Fertilizers, Department of Chemicals and Petrochemicals, Statistics and Monitoring Division

Outlook for lithium exploration, production and trade in India

Atomic Minerals Directorate for Exploration and Research (AMD) is carrying out exploration for lithium in potential geological domains in parts of Mandya and Yadgir districts of Karnataka. Preliminary surveys on surface and limited subsurface exploration by AMD have shown presence of lithium resources of 1,600 tons (inferred category) in Marlagalla area, Mandya district, Karnataka. Further, the Geological Survey of India (GSI), Ministry of Mines, takes up different stages of mineral exploration as per the approved annual Field Season Program (FSP) every year viz. reconnaissance surveys (G4), preliminary exploration (G3) and general exploration (G2) following the guidelines of the United Nations Framework Classification (UNFC) and the Mineral Evidence and Mineral Content Rules (MEMC-2015). The GSI undertook the FSP to augment mineral resource for various mineral commodities, including lithium. During FSP 2016–17 to FSP 2020–21, GSI carried out 14 projects on lithium and associated elements in Bihar, Chhattisgarh, Himachal Pradesh, Jammu and Kashmir, Jharkhand, Madhya Pradesh, Meghalaya, Karnataka and Rajasthan. During the current FSP 2021–22, GSI has taken up five projects on lithium and associated minerals in Arunachal Pradesh, Andhra Pradesh, Chhattisgarh, Jammu and Kashmir and Rajasthan. In Feb'23, GSI established lithium inferred resources (G3) of 5.9 million tons in the Salal-Haimana area of the Reasi District of Jammu & Kashmir (UT).

Total Import of lithium commodities

Year	2019-20	2020-21	2021-22
	Rs. crore	Rs. crore	Rs. crore
Lithium (HS Code: 85065000)	147	173	165
Lithium-ion (HS Code: 85076000)	8,819	8,811	13,673
Mineral substances not elsewhere specified or included (HS code: 2530)	340	283	498

Country-wise import of lithium

	2018-19		2019-20		2020-21	
Country	Quantity	%Share Country	Quantity	%Share Country	Quantity	%Share Country
Hong Kong	47,248	55	38,547	53	26,641	37
China	16,868	20	14,988	21	22,881	32
Indonesia	11,276	13	9,063	13	6,689	9
Singapore	4,929	6	5,077	7	5,849	8
Korea RP	3,257	4	2,780	4	5,090	7
Japan	1,134	1	1,512	2	3,180	4
Israel	186	0	144	0	337	0
US	84	0	85	0	243	0
Malaysia	70	0	72	0	155	0
Taiwan	42	0	61	0	126	0
Others (26 Countries)	130	0	48	0	202	0
Total	85,224	100	72,376	100	71,392	100

Source: https://tradestat.commerce.gov.in/

Nickel is not produced from primary sources in India and the demand is largely met through imports

Hindustan Copper Limited (HCL) is utilizing advanced technology to extract nickel, copper, and sulfuric acid from the spent electrolyte (waste stream) of the ICC refinery located in Ghatsila, Jharkhand.

Nickel resources in India are estimated at 189 million tons and are primarily found as oxides, sulfides, and silicates. The State of Odisha possesses the largest share of nickel ore resources in the country, estimated at 175 million tons (93%), followed by Jharkhand and Nagaland. These resources are concentrated in three districts, namely, Jajpur (140 million tons), Mayurbhanj (27 million tons) and Keonjhar (8 million tons).

At its Ghatsila Copper Smelter in Jharkhand, HCL produces nickel sulfate as a by-product. The sulfide copper ore from the Ghatsila area contains nickel in small quantity along with other important metals like gold and cobalt. Using imported EMEW technology from Canada, HCL has developed the capability to recover LME-Nickel grade cathode from a lower copper concentration in spent electrolyte, which is not possible using conventional means. This technology also enables HCL to recover nickel from the spent electrolyte at the ICC refinery. In addition, HCL utilizes an eco-friendly Acid Purification Unit (APU) technology imported from Canada to reduce liquid effluent and facilitate downstream recovery of nickel. HCL has a capacity of 390 million tons to recover nickel sulfate, but no production of nickel sulfate has been reported since 2004-05. Nicomet Industries Ltd., located in Goa, presently produces nickel metal and their derivatives with an annual production capacity of about 5,400 MTPA.

Recently, Hindustan Copper Limited (HCL) has launched India's first nickel production facility at its Indian Copper Complex (ICC) in Ghatsila, Jharkhand to reduce India's dependence on imported nickel.

The Hindustan Copper Limited (HCL) and it is at its Indian Copper Complex (ICC) has launched the "Nickel, Copper and Acid Recovery Plant," which is the first facility in India to produce London Metal Exchange (LME) grade nickel metal from primary resources. NMDC has applied to the DMG, Government of Odisha, for the reservation of an 8-square kilometer area in Jajpur district, Odisha, under Section 17A (2A) of MM(D&R) Amendment Act, 2015, for nickel prospecting and mining operations.

An Indian delegation, led by Dr. V.K. Saraswat, Member, NITI Aayog, explored opportunities for sourcing lithium for the manufacture of advanced chemistry batteries in India during their visit to Chile, Argentina, and Bolivia. The delegation engaged in talks with the Western Australia Premier and discussed forming strategic collaborations to source raw materials, including lithium, cobalt, and nickel to aid in the manufacturing of batteries.

The mobility mission had consultations with the industry to develop battery recycling as a sustainable method to ensure the 95% of recovery of critical minerals such as lithium, nickel, and cobalt. The CSIR-IMMT has developed suitable process flow sheets for processing resources such as alloy scrap and a spent catalyst to produce precursor materials for battery applications, primarily in preparing electrodes of Li-ion batteries. India will have to depend on imports until a commercial-scale technology for recovering nickel from the overburden of chromite ore in Odisha is established.
The HCL's process for producing primary nickel from copper refining waste will be a breakthrough in nickel production in the country. Recycling nickel-bearing scrap in the Organized Sector will be another source for meeting demand.

Imports of nickel ores and concentrates (Heading no. 2604) and nickel waste and scrap (Heading no. 75030010) are allowed free as per the Foreign Trade Policy, 2015-2020. However, some forms of metal waste and scrap (ITC-HS Code No. 7503 0090) are restricted.

Source: Indian Minerals Yearbook 2020, (Part- II: Metals and Alloys); 59th Edition, Nickel, INDIAN BUREAU OF MINES, August 2021

Cobalt production is limited in India and the demand is largely met through imports

Currently, India does not produce cobalt from primary resources and relies on imports to meet demand. The reserves/resources of cobalt in terms of ore have been estimated at 44.91 million tons, of which about 69%, i.e., 30.91 million tons are estimated in Odisha. The remaining 31% resources are in Jharkhand (9 million tons) and Nagaland (5 million tons). Cobalt refining capacity is estimated at ~2,060 tons per year, with Nicomet Industries Ltd, Cuncolim, Goa and Rubamin Ltd., Vadodara, Gujarat being the leading producers of cobalt cathodes and compounds. Nicomet has 1,000 tons per year (tpa) installed capacity for cobalt metal and different cobalt salts.

Nicomet Industries Ltd produces LME-approved cobalt cathodes under the NICO brand, along with nickel cathodes and sodium sulfate in Mumbai, Maharashtra. Vedanta Group is also exploring ways to produce cobalt for batteries as it seeks to capitalize on the anticipated electric vehicle boom. Sandvik Asia Ltd reportedly recovers cobalt metal powder from cemented carbide scrap at its pilot plant in Pune, Maharashtra. Several small cobalt chemical processors reprocess spent cobalt catalyst from plants to produce DMT, TPA and oxo alcohols. However, information on reprocessing of cobalt from scrap is not available. It is expected that recycled cobalt would continue to be used for domestic supply.

With India's rising trend in cobalt consumption, it is important to recover cobalt from various secondary sources. Hindustan Zinc Ltd has explored a lab-scale process for recovering cobalt from purification cake, generating a 60% purity cobalt sulfate crystal with 50% recovery. Although India lacks primary cobalt resources, there are two potential secondary sources that have been the subject of R&D studies for commercial applications over the years: nickel-bearing laterite deposits in Odisha and copper slag produced by HCL.

In India, cobalt refiners have mainly served the market for chemical applications where cobalt metal or salt is dissolved and converted to cobalt oxide for cutting tool applications.

However, the global demand for cobalt is expected to increase significantly, especially for use in cemented carbides used in cutting tools, catalysts in the petrochemical industry, drying agents in the paint industry, and superalloys used mainly in jet engine parts. The demand for cobalt is also projected to increase rapidly in rechargeable batteries for hybrid electric vehicles, cellular telephones, aerospace, superalloys in civil aviation, catalysts for gas-to-liquid production of synthetic liquid fuels and energy generation industries. The surge in demand for mobile phones, portable PCs, and other electronic devices has led to a rapid growth in the global demand for lithium-ion batteries. The projected demand for refined electronic devices is also massive. According to CRU, the demand for cobalt is expected to grow by an astonishing rate of 68% between 2015 and 2025.

In India, cobalt will have significant applications in metallurgy due to increased demand for special alloys/superalloys, cutting tools, and as an alloy in permanent magnets. The demand for cobalt powder will continue to increase as it is widely used in the production of bonded tools for the diamond industry.
While the Indian cobalt industry is small, it is steadily growing in various sectors, especially in aerospace. The Aerospace Industry mainly relies on cobalt imports. Although other industries are growing consistently, they cannot be compared to China. The total consumption of cobalt content in India could range from 70 to 80 tons minimum and up to 100 tons maximum per month. Chemical industries mostly use cobalt sulfate. Battery manufacturing is a significant sector with immense potential in India, which could trigger the development of new technology and product upgrades.

Source: Indian Minerals Yearbook 2020, (Part- II: Metals and Alloys); 59th Edition, Nickel, INDIAN BUREAU OF MINES, August 2021

Natural graphite mining and beneficiation industry in india

Graphite is a hexagonal crystal that occurs in layered and lamellar form with a greasy texture and gray-black metallic luster. There are two commercial varieties of natural graphite: crystalline (flaky) and amorphous. Both flaky and amorphous graphite are produced in India and their quality is determined by their carbon content and physical properties. Additionally, synthetic or artificial graphite is manufactured using anthracite or petroleum coke as raw feed.

Graphite deposits of economic importance are located in Chhattisgarh, Jharkhand, Odisha, and Tamil Nadu. In the year 2019-20, the production of graphite decreased by 18% as compared to the previous year, with five principal producers accounting for 96% of the total production. The number of mines remained the same as 11 in 2019-20 and 2018-19. During the 2019-20 period, two mines that produce over 5,000 tons annually accounted for 61% of the total graphite production, while four mines that produced between 1,000 and 5,000 tons annually contributed to 39% of the total. The state of Jharkhand was the top producer, contributing 61% to the total output, followed by Odisha.

The top producing states were Jharkhand and Odisha, and the active mining centers of graphite are Palamu district in Jharkhand, Nawapara and Balangir districts in Odisha, and Madurai and Sivagangai districts in Tamil Nadu. In Jharkhand, disseminated deposits of flaky graphite containing 5 to 20% fixed carbon (F.C.) are found in the Palamu district, while in Odisha, several graphite grades are produced in areas in and around Balangir.

The graphite deposits are relatively soft and the presence of hard rocks on both sides makes mining a relatively easy and safe process. The top layer of lateritic soil, typically one to two meters thick, is removed using a dozer or excavator and loaded onto a dumper for transportation to a separate dump yard in the lease area that is not mineralized. The extracted graphite ore is then transported to a stockyard for blending, with high-grade and low-grade ores stacked separately. After blending, the ore is dispatched for consumption, depending on plant requirements.

Maximizing the recovery of flaky graphite from low-grade graphite ore during beneficiation is a significant challenge as breaking the flakes would reduce the graphite's unique properties, such as excellent lubricity and high thermal conductivity, which are in high demand in the industry. Graphite requires beneficiation to obtain the desired grade for various end-uses, usually occurring mixed with country rocks. Processes for graphite beneficiation include washing, sorting, tabling, acid leaching, and froth flotation. Froth flotation is commonly used to produce a high-grade graphite concentrate. The beneficiated concentrate is sometimes further enriched by chemical treatment (acid leaching, chlorination, etc.) to obtain a high-grade concentrate containing 98% to 99% Fixed Carbon (F.C.).

Source: Indian Minerals Yearbook 2020, (Part- II: Metals and Alloys); 59th Edition, Nickel, INDIAN BUREAU OF MINES, August 2021

Grade wise natural graphite production and end-use consumption

State/District	No. of Mines	2019-20				
		Grade: Fixed Carbon content			Total	
		80% or more	40% or more but less than 80%	Less than 40%	Quantity	Value
India	11	615	651	30,725	31,991	57,506
Public Sector	2	-	-	-	-	-
Private Sector	9	615	651	30,725	31,991	57,506
Chhattisgarh	1*	-	-	-	-	-
Surguja	1*	-	-	-	-	-
Jharkhand	3	-	-	19,426	19,426	20,380
Latehar	1	-	-	4,676	4,676	4,730
Palamau	2	-	-	14,750	14,750	15,650
Karnataka	2*	-	-	-	-	-
Mysore	2*	-	-	-	-	-
Kerala	-	-	-	-	-	-
Ernakulum	-	-	-	-	-	-
Odisha	5	615	651	11,299	12,565	37,126
Nawapara	2	-	-	11,299	11,299	12,099
Raygada	3	615	651	-	1,266	25,027
Tamil Nadu	-	-	-	-	-	-
Madurai	-	-	-	-	-	-
Sivagangai	-	-	-	-	-	-
						‘8hmn

Source: Indian Minerals Yearbook 2020, (Part- II: Metals and Alloys); 59th Edition, Nickel, INDIAN BUREAU OF MINES, August 2021

Spherical graphite, also known as battery-grade graphite, is the specific commodity used in the production of anode in lithium-ion batteries. Flake graphite concentrate is processed into ultra-high-purity (>99.95% C), microscopic (15 to 5 microns) spheres, which are used as a battery anode material. This decreases the surface area, to allow more graphite into a smaller volume, thus creating a compact, lighter, more electrically conductive anode product for the battery.

Quantity in tons, Value in Thousand INR

End Product	Percentage of graphite used	Quality of the graphite used	
		Fixed Carbon	Size (micron)
Mag-Carb refractories	12	87-90%	150-710
Alumina-Carb (graphitized) alumina refractories	8-1085%	min.	150-500
Clay-bonded crucibles	60-65	+80%	-20 to +100 mesh
Silicon carbide crucibles	35	80-89%	+150
Expanded (or flexible) graphite foils and products (e.g. sealing gaskets in refineries)	100	90% min. (preferably +99%)	250-1800
Pencils	50-60	94	50 max.
Brake-linings	1-15	98% min.	75 max.
Foundry	-	40-70%	53-75
Batteries - Dry cells	-	88% min.	75 max.
Batteries - Alkaline	-	98% min.	5-75
Brushes	-	Usually 99%	Usually less than 53
Lubricants	-	98-99%	53-106
Sintered products (e.g. clog wheels)	-	98-99%	5
Paint	Up to 75	50-55% 75% min.	Amorphous powder Flake
Braid used for sealing (e.g. in ship)	40-50	95% min.	-
Graphitized grease (used in seamless steel tube manufacturing)	-	+99%	38 max.
Colloidal graphite	100	99.9%	Colloidal

From the above statistics, one can infer that the Spherical graphite processing industry produced from flake concentrates as feedstock is still at nascent stages.

Production and consumption of manganese ore in India

Quantity in tons, Value in Thousand INR

Slate	2017-18		2018-19		2019-20	
	Quantity	Value	Quantity	Value	Quantity	Value
Andhra Pradesh	172,174	706,314	293,679	1,039,486	331,030	1,317,483
Gujarat	18,362	11,496	-	-	-	-
Jharkhand	4,783	44,527	4,785	39,839	4,785	35,577
Karnataka	294,261	1,541,069	332,162	2,276,289	333,425	2,284,994
Madhya Pradesh	837,041	6,760,106	942,738	7,147,719	958,164	6,160,735
Maharashtra	731,457	7,243,631	761,985	7,999,939	721,520	6,127,232
Odisha	516,862	3,497,593	476,821	3,048,997	537,742	3,409,984
Rajasthan	7,502	22,506	9,410	28,230	9,937	29,811
Telangana	17,373	80,232	10,735	59,666	7,770	50,570
India	2,599,815	19,907,474	2,832,315	21,640,165	2,904,373	19,416,386

Quantity in tons

Industry	2017-18	2018-19	2109-20
Ferroalloys	2,538,100	2,695,900	2,387,600
Iron and steel	128,100	167,700	204,200
Others: (Chemical, Electrode, Pelletization, Sponge Iron, etc.)	35,500	22,400	24,200
All Industries	27,017,000	2,886,000	2,616,000

* The apparent consumption of manganese ore in 2019-20 is estimated at 6.9 million tons

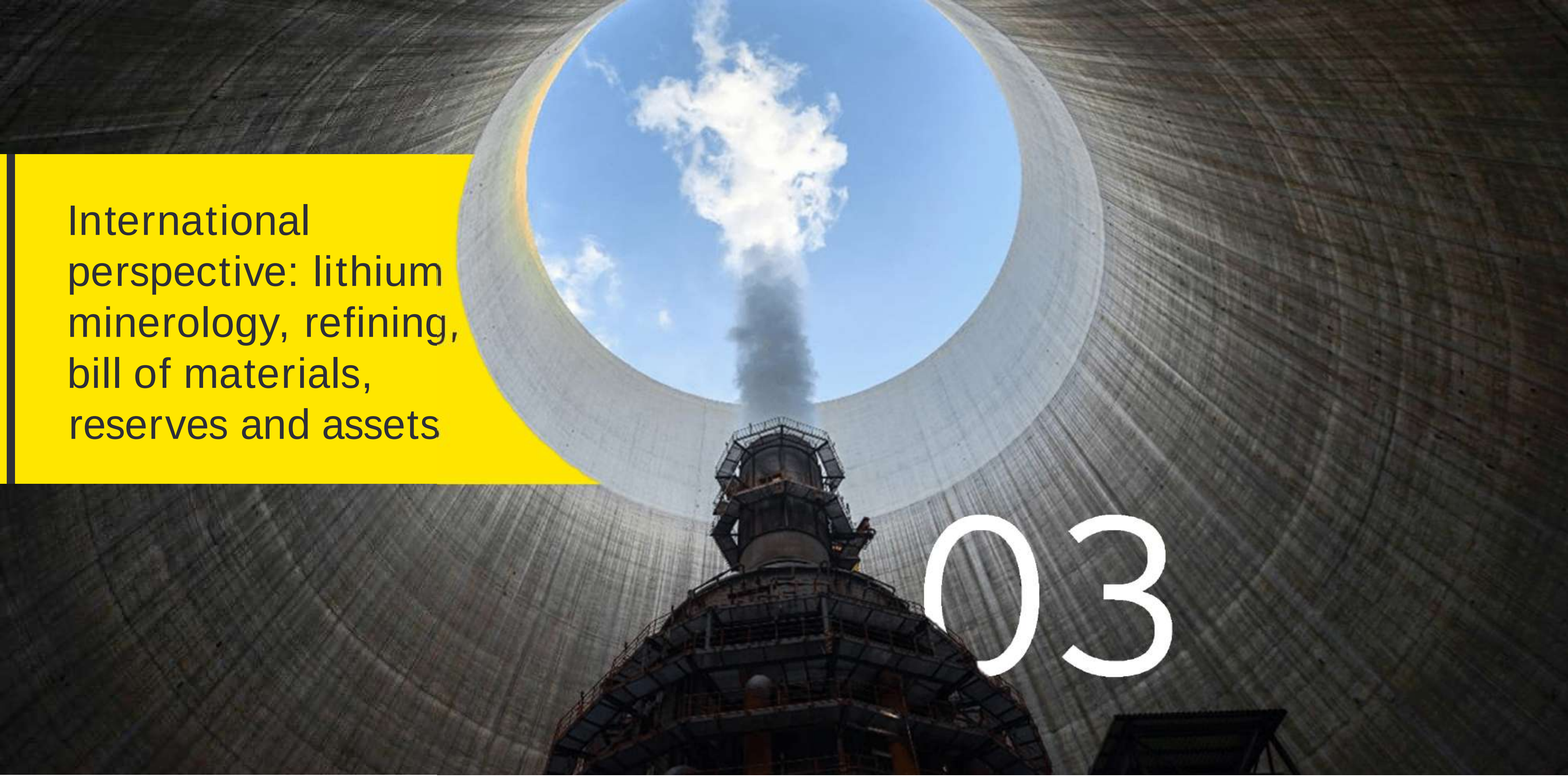
The consumption of manganese ore in all industries was about 2.62 million tons in 2019–20.

Ferroalloys industries accounted for about 91% consumption followed by Iron and Steel (8%).

Battery, Electrode, Chemical, Zinc Smelter and Alloy Steel industries shared the remaining 1%.

MOIL had set up a High Intensity Magnetic Separation Plant and 1,000 tons per year (tpy) Electrolytic Manganese Dioxide (EMD) Plant at Dongri Buzurg mine. In 2019-20, about 925 tons of EMD were produced.

Source: Indian Minerals Yearbook 2020, (Part- I: General Reviews); 59th Edition, MINERAL-BASED INDUSTRIES, INDIAN BUREAU OF MINES, September 2022



International perspective: lithium minerology, refining, bill of materials, reserves and assets

03

Minerology of lithium

Lithium is commonly extracted from two major categories of economic mineral deposits: pegmatites and brines. Extraction from volcanic clays containing Li rich hectorite is yet to be demonstrated on a commercial scale. Lithium concentrations are typically measured in parts per million (ppm), milligrams per liter (mg/L) and weight percentage. Lithium concentrations in the earth’s upper crust are 20 ppm (average). In igneous rocks, the abundance is typically from 28 to 30 ppm, but in sedimentary rocks, it can be as high as 53 to 60 ppm.

Li bearing mineral	Chemical Formula	Li % (max.)	Occurrence
Spodumene	Li2O, Al2O3. 4SiO2	~4 %	Most abundant Li bearing mineral found in economic deposits, occurs as crystals in granites and pegmatites often intermixed with quartz
Lepidolite	K2 (Li,Al)5-6 {Si6-7Al2-1O20} (OH,F)4	~3.6%	Uncommon form of mica found in pegmatites
Petalite	Li2O, Al2O3. 8SiO2	~2.3%	Occurs with lepidolite in pegmatites and could alter to Spodumene
Hectorite	Na0.3 (Mg,Li)3 Si4O10 (OH)2	~0.5%	Trioctahedral smectite clay mineral formed by alternation of volcanistic rocks by hydrothermal activity
Jadarite	LiNaSiB3O7 (OH)	~7%	Occurs as borosilicate mineral discovered in Serbia

Source: EY analysis based on British Geological Survey, Natural Environment Research Council, June 2016
Note: Li to Li2O conversion factor is 2.153; Li to Li2CO3 conversion factor is 5.323; 1% weight is equivalent to 10,000 ppm

Lithium bearing brine resources	Type	Li concentration
Seawater		0.1 – 0.2 ppm
Clayton Valley, Nevada (Silver Peak)	Continental brine	400 ppm
Salar de Atacama, Chile	Continental brine	1000 – 4000 ppm
Salar de Hombre, Argentina	Continental brine	190 – 900 ppm
Salar de Olaroz, Argentina	Continental brine	500 ppm (mean)
Salar de Rincon, Argentina	Continental brine	330 ppm
Salton Sea, California	Geothermal brine	100 – 200 ppm
Smackover oilfield, Arkansas	Oilfield brine	500 ppm

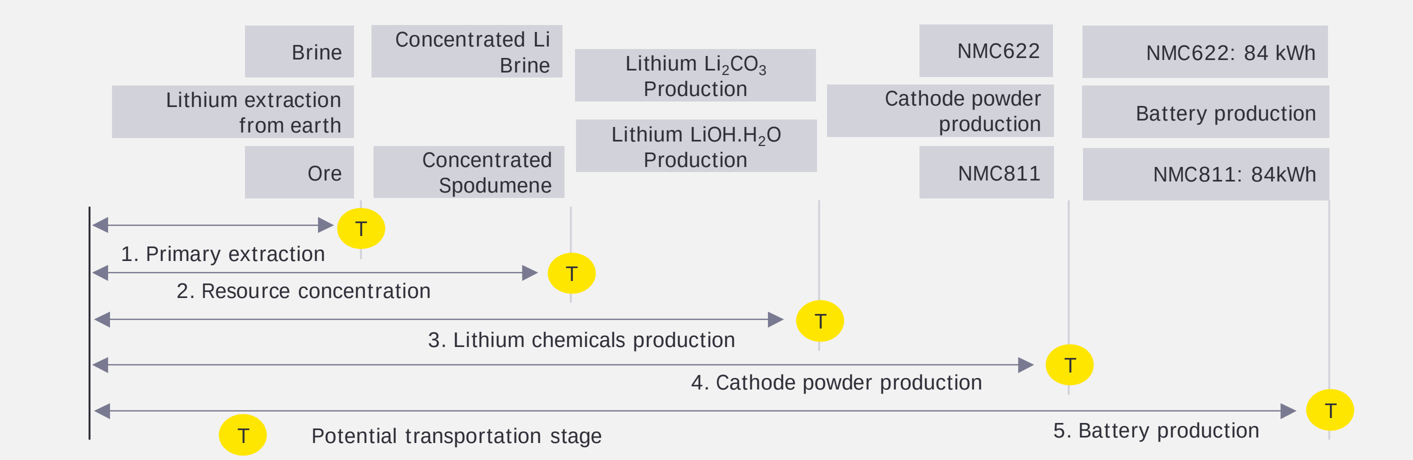
Source: British Geological Survey, Natural Environment Research Council, June 2016

Brine refers to any fluid containing a high level of dissolved solids. Lithium occurs in many brines but usually at low concentrations. Commercial extraction from brines primarily occurs from continental brine deposits.

Spodumene has a theoretical Li2O content of 8.03%. A typical run of mine spodumene ore can contain ~1% Li2O (eq. 0.46% Li or ~5000 ppm), while a typical spodumene concentrate suitable for lithium carbonate production contains 5% to 6% of Li2O (75% - 87% spodumene). Higher grade concentrates > 7% Li2O and low-iron content are used in ceramics and more demanding industries. The addition of lithium imparts high mechanical strength and thermal shock resistance in ceramics and glass.

Processing spodumene mineral to battery grade lithium carbonate / hydroxide

Potential transportation stages in lithium lifecycle



Brine

Concentrated Li Brine

Lithium extraction from earth

Ore

Concentrated Spodumene

Lithium Li_2CO_3 Production

Lithium $LiOH.H_2O$ Production

NMC622

Cathode powder production

NMC811

NMC622: 84 kWh

Battery production

NMC811: 84kWh

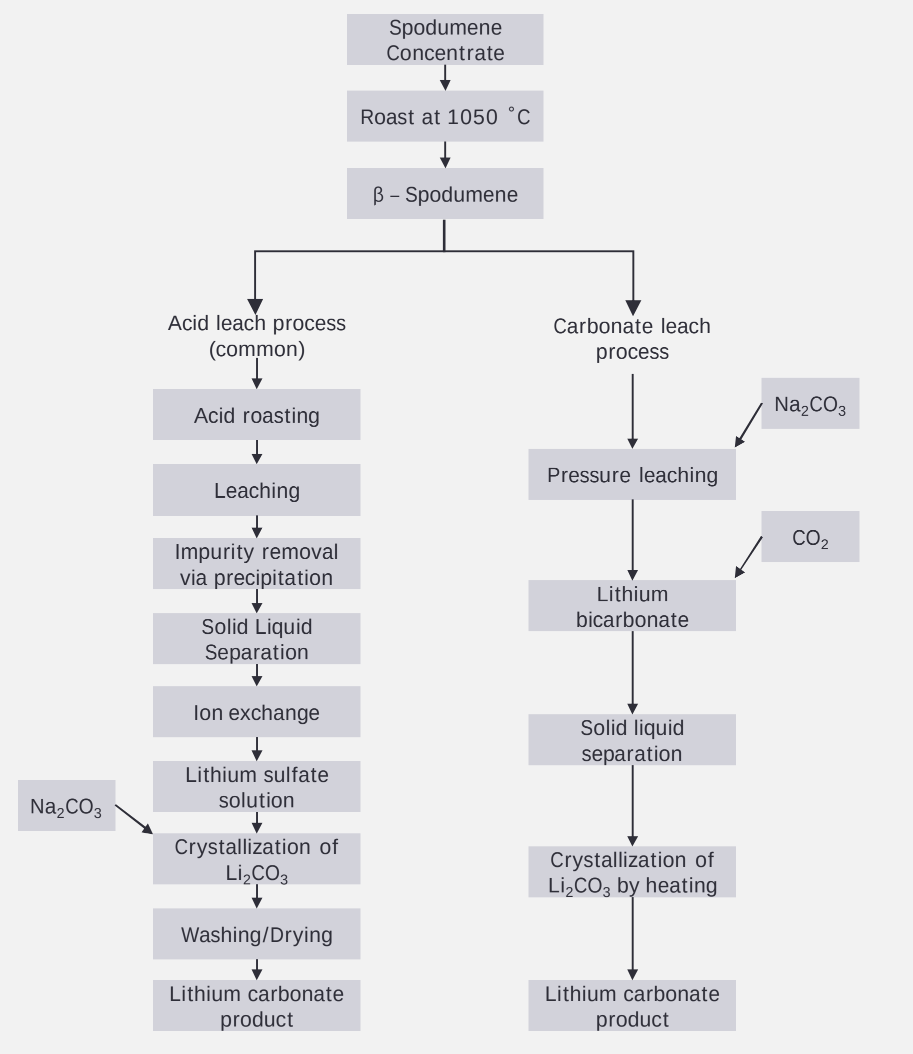
1. Primary extraction
2. Resource concentration
3. Lithium chemicals production
4. Cathode powder production
5. Battery production

T Potential transportation stage

Beneficiation / concentration (Spodumene)	• Crushing and grinding of large sized pieces of ore into smaller pieces and separating on the basis of their physical, chemical and magnetic properties • Removal of clay, silicate minerals and other gangue materials using froth floatation or dense media separation or a combination of both to obtain ~6% Li2O concentration
Roasting	•Heating in a kiln at 1050°C for 15 min. to convert naturally occurring α-spodumene (monoclinic structure) to β-spodumene (tetragonal structure) which is chemically active to leaching
Leaching	•Heating in presence of air at 250°C with addition of H_2SO_4 to obtain lithium sulfate •In addition to lithium sulfate, impurities such as Fe, Al and Ca are also leached out as sulfates
Filtration and purification	•Addition of water to precipitate the impurities of Fe and Al •Lithium sulfate solution is filtered with trace levels of impurities of Mg and Ca
Carbonation	•Solution is treated with Na_2CO_3 to precipitate insoluble insoluble Li_2CO_3 •The precipitate is washed and dried to obtain 99.3% lithium carbonate

Source: Lithium Production Processes – ScienceDirect, Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries – ScienceDirect

Spodumene processing flow chart



Spodumene Concentrate

Roast at 1050 ˚C

β – Spodumene

Acid leach process (common)

Acid roasting

Leaching

Impurity removal via precipitation

Solid Liquid Separation

Ion exchange

Lithium sulfate solution

Na_2CO_3

Crystallization of Li_2CO_3

Washing/Drying

Lithium carbonate product

Carbonate leach process

Na_2CO_3

Pressure leaching

CO_2

Lithium bicarbonate

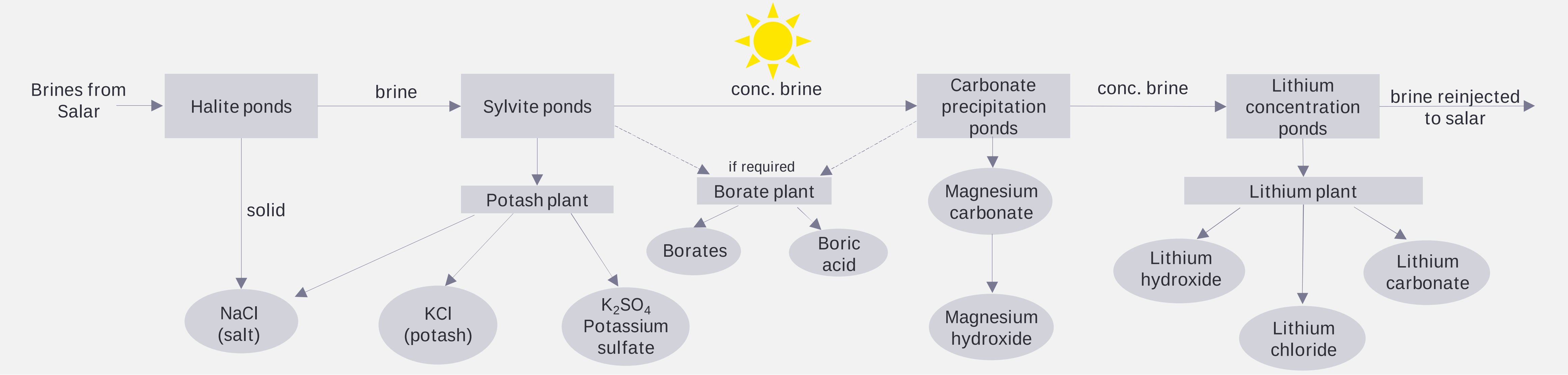
Solid liquid separation

Crystallization of Li_2CO_3 by heating

Lithium carbonate product

Processing continental brine to battery grade lithium carbonate / hydroxide

Continental Brine to Lithium carbonate/hydroxide conversion



Brines from Salar

Halite ponds

brine

Sylvite ponds

conc. brine

Carbonate precipitation ponds

conc. brine

Lithium concentration ponds

brine reinjected to salar

solid

Potash plant

if required

Borate plant

Magnesium carbonate

Lithium plant

Borates

Boric acid

Lithium hydroxide

Lithium carbonate

NaCl (salt)

KCl (potash)

K_2SO_4 Potassium sulfate

Magnesium hydroxide

Lithium chloride

Beneficiation / Concentration (Brine)	•Lithium is Brine (1% lithium con.) is pumped out and poured into solar evaporation pond •Sodium chloride is precipitated first, brine is then transferred to another set of ponds in which mixture of NaCl (salt) and KCl (sylvinite) is precipitated •Remaining brine is piped to another set of ponds where it remains until concentration reaches to 6000 ppm Li and then transferred to recovery plant
Boron and magnesium removal	•Concentrated brines is rich in boron and magnesium •Boron is removed by solvent extraction using kerosene and processed to produce borated and boric acid •Magnesium is removed by adding Na_2CO_3 to precipitate Magnesium carbonate, lime is then added to precipitate magnesium hydroxide
Precipitation and filtration of Li_2CO3	•Lithium rich brine is treated with sodium carbonate to precipitate Li_2CO_3 slurry •This is filtered and washed with water to remove residual NaCl and dried to obtain >99% lithium carbonate
Conversion to $LiOH.H_2O$	•Lithium carbonate is further treated with CaO and water to produce $LiOH.H_2O$

Source: Lithium Production Processes – ScienceDirect

Lifecycle energy and material intensity of lithium extraction and chemical processing

Brine → Con. Brine

Material and energy flow by allocation methods for per ton of concentrated brine (6% lithium) produced in the Salar de Atacama					
Per ton concentrated brine	Unit	Facility Level (mass)	Facility Level (value)	Product Level	Product Process
Materials input					
Lithium brine	ton	24.1	24.1	24.1	24.1
Fresh water	m^3	2.40	5.94	3.72	2.35
Energy input					
Electricity	MJ	307	760	624	472
Diesel	MJ	265	657	346	327
Coproduct					
Potash	ton	8.52	8.52	8.52	8.52
By-product (as stock in the system)					
Lithium	ton as LCE	0.80	0.80	0.80	0.80

Con. Brine → Li_2CO_3

Material and energy flow per ton of Li_2CO_3		
Per ton Li_2CO_3	Input	Unit
Materials input		
Lithium brine (6% Li)	4.00	ton
Soda ash	2.00	ton
Other[a]	0.08	ton
Energy input		
Electricity	1,500	MJ
Diesel	400	MJ
Natural gas	2,800	MJ
Non-combustion emissions		
PM 10	700	g
PM 2.5	400	g

[a] Includes H2SO4, HCl, lime, solvent, and alcohol.

Li_2CO_3 → LiOH.H_2O

Material and energy flow per ton of LiOH.H2O		
Per ton LiOH•H_2O	Input	Unit
Materials input		
Li_2CO_3	1.05	ton
CaO	1.15	ton
Water consumed	0.50	m^3
Energy input		
Electricity	5,000	MJ
Diesel	3,000	MJ
Natural gas	21,000	MJ
Non-combustion emissions		
PM 10	100	g
PM 2.5	50	g

Brine to concentrated brine

- Diesel used for vehicles (23%) and generating power for operations (77%)
- Stored lithium is treated as stock rather than a coproduct, which will eventually be recovered for value
- Concentrated lithium brine has three times the value of potash

Concentrated brine to Li_2CO_3

- Trucks with 24.5 tons payload used to transport concentrated brine to facility
- Water used is a fully recycled stream

Mineral ore to concentrated spodumene

- Concentration of ore in western Australia
- Material movement from mine to facility in diesel trucks (22 tons payload)
- Plant running on diesel fuel
- Produced concentrated spodumene ore is 63% pure spodumene (5% Li_2O)

Concentrated spodumene to LiOH.H_2O/Li_2CO_3

- Spodumene shipped from Australia to China and transported by truck to facility
- 12 tons of steam per ton of LiOH.H_2O, 16.5 tons of steam per tons of Li_2CO_3

Source: Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries – ScienceDirect

Ore → Con. Spodumene

Material, energy, and water inputs per ton of concentrated spodumene produced		
Per ton concentrated spodumene	Quantity	Units
Materials input		
Spodumene ore (0.8–0.9% conc.)	4.50	ton
Other[a]	0.015	ton
Fresh water	3	m3
Energy input		
Diesel	4,500	MJ

[a] Includes sodium carbonate and a dispersant.

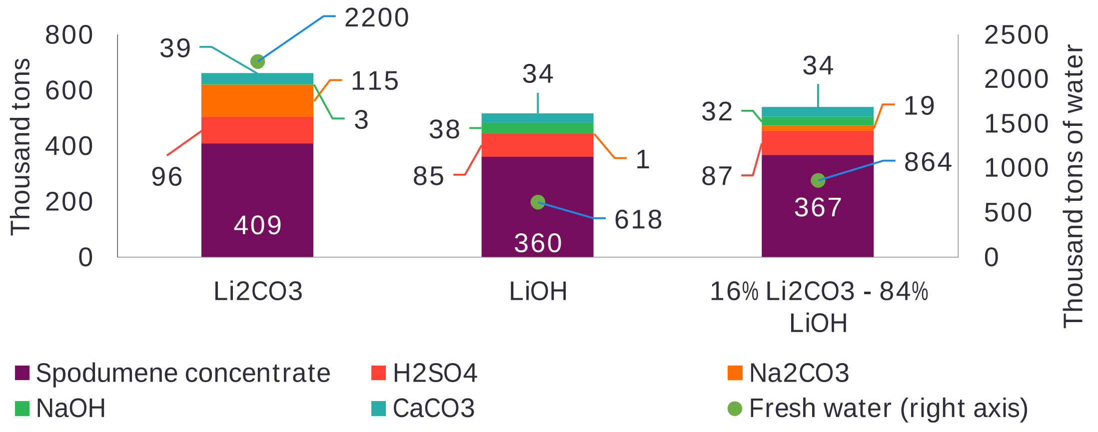
Con. Spodumene → LiOH.H_2O/Li_2CO_3

Material and energy flow per ton of LiOH•H_2O and Li_2CO_3 produced in China from Australian spodumene concentrate			
	Input Per ton LiOH•H2O	Input Per ton Li2CO3	Unit
Materials input			
Spodumene concentrate (6% Li_2O)	6.42	7.30	ton
H2SO4 (98% conc.)	1.52	1.71	ton
Na_2CO_3 (98.8% conc.)	0.025	2.05	ton
NaOH (96% conc.)	1.18	0.05	ton
$CaCO_3$ (≥ 98% conc.)	0.6	0.7	ton
Fresh water	11.24	40	m^3
Energy input			
Electricity (China grid)	12,600	6,480	MJ
Coal (for LiOH•H_2O)[a]	71,343	–	MJ
Coal (for Li_2CO_3)[b]	–	135,890	MJ
By-product output			
Na_2SO_4	1.72	1.92	ton

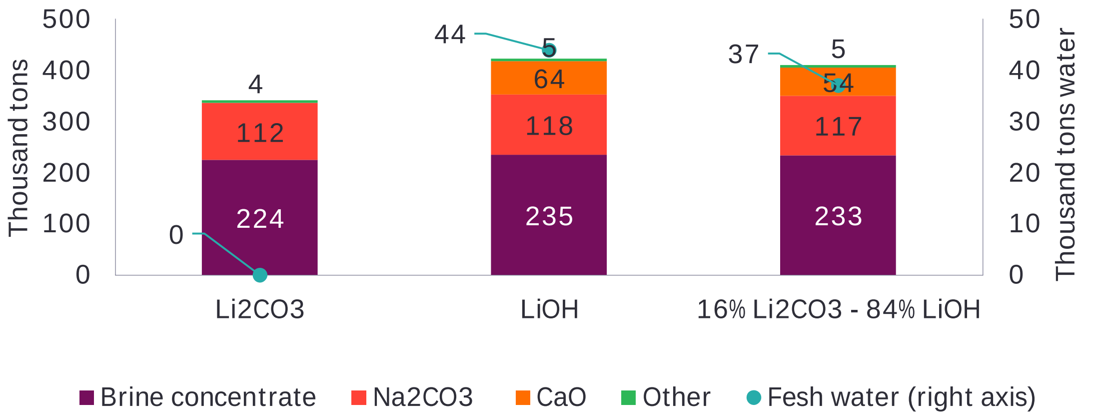
[a] 54% for steam and 46% for kiln.
[b] 39% for steam and 61% for kiln.

Material and energy intensity of lithium carbonate/ hydroxide production by 2030

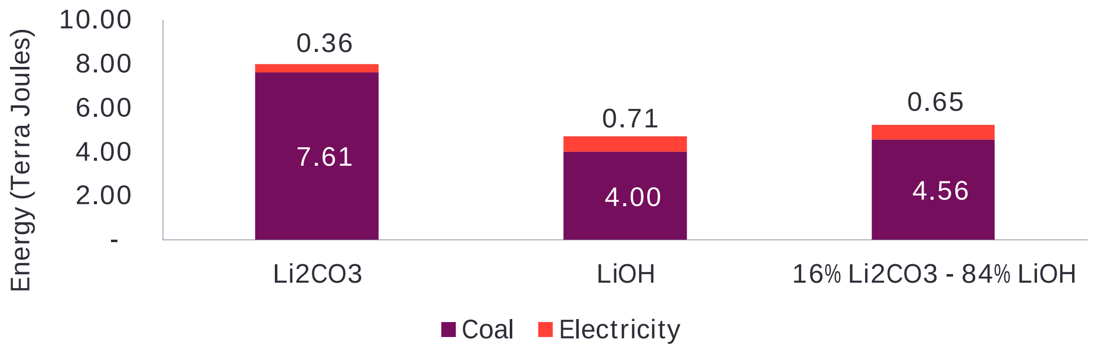
Precursors for producing 56,000 tons/annum Li2CO3/LiOH from spodumene (100 GWh/annum LIBs)



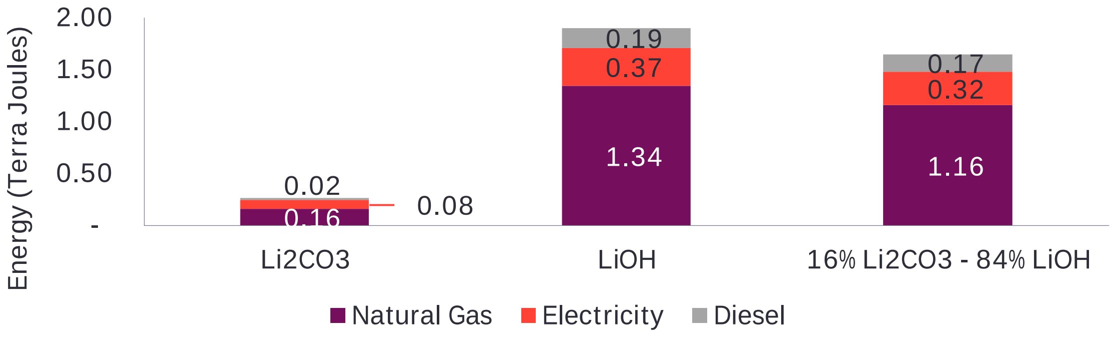
Precursors for producing 56,000 tons/annum Li2CO3/LiOH from brine (100 GWh/annum LIBs)



Energy for producing 56,000 tons/annum Li2CO3/LiOH from spodumene (100 GWh/annum LIBs)

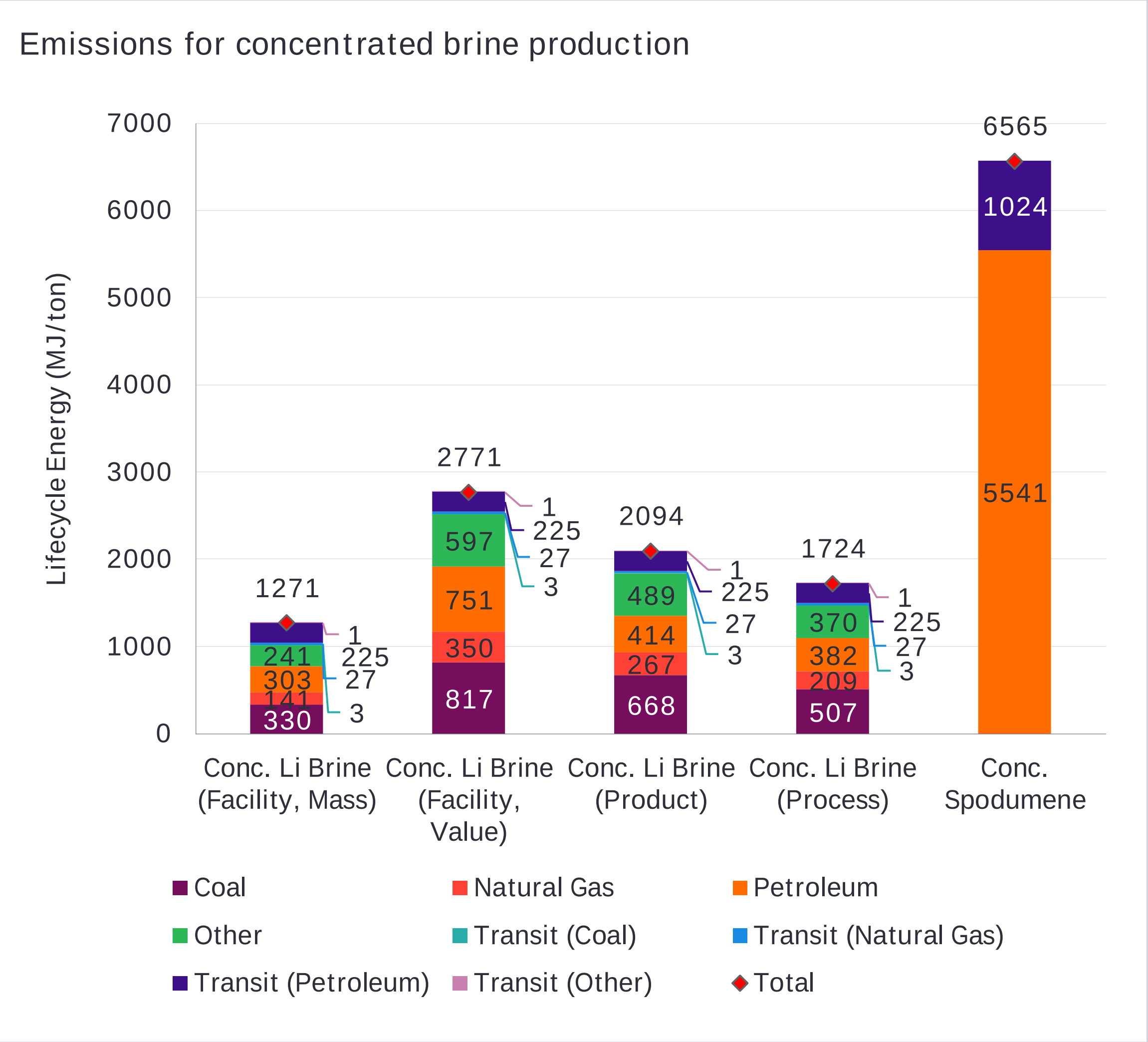


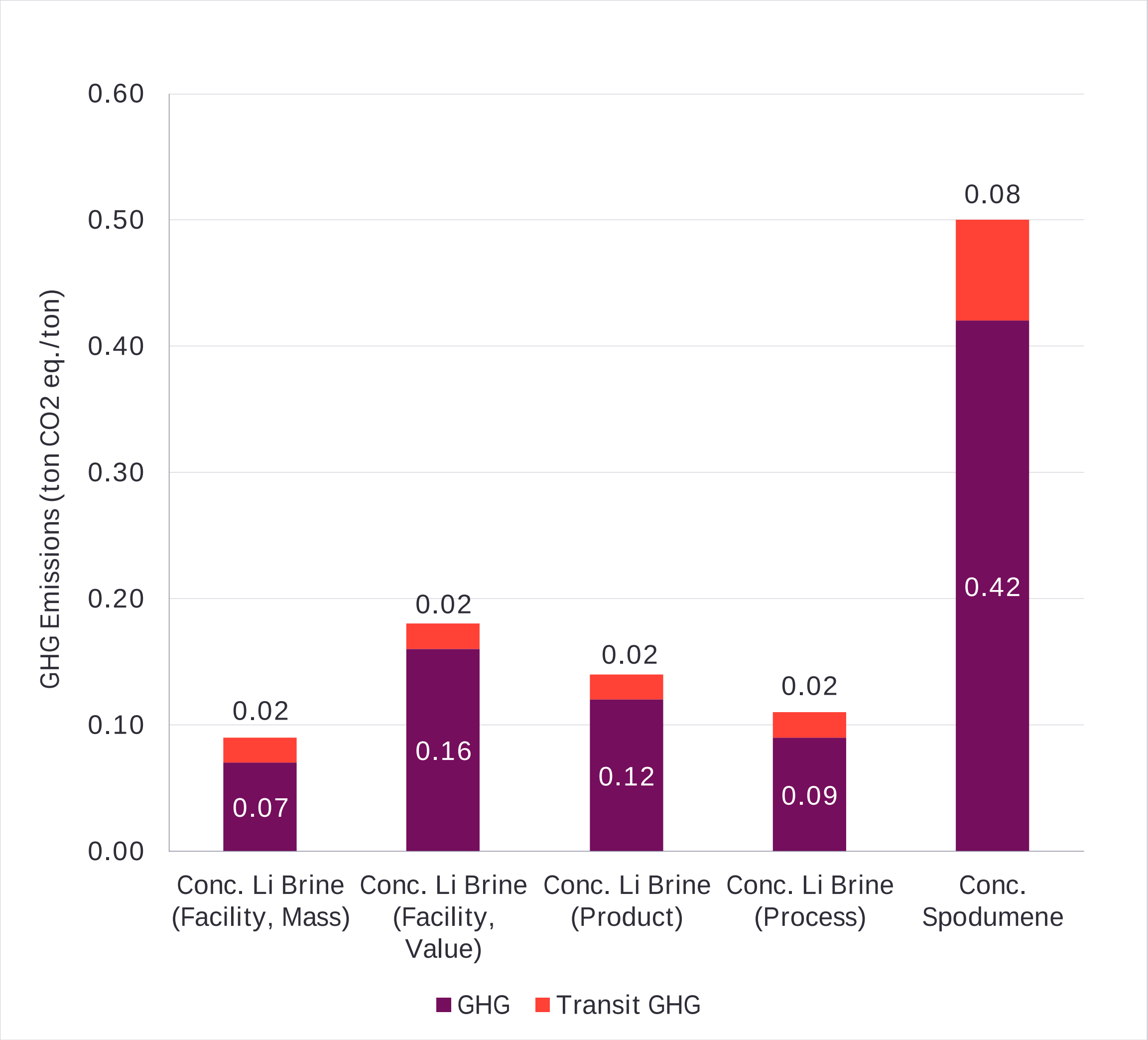
Energy for producing 56,000 tons/annum Li2CO3/LiOH from brine (100 GWh/annum LIBs)



Source: EY Analysis

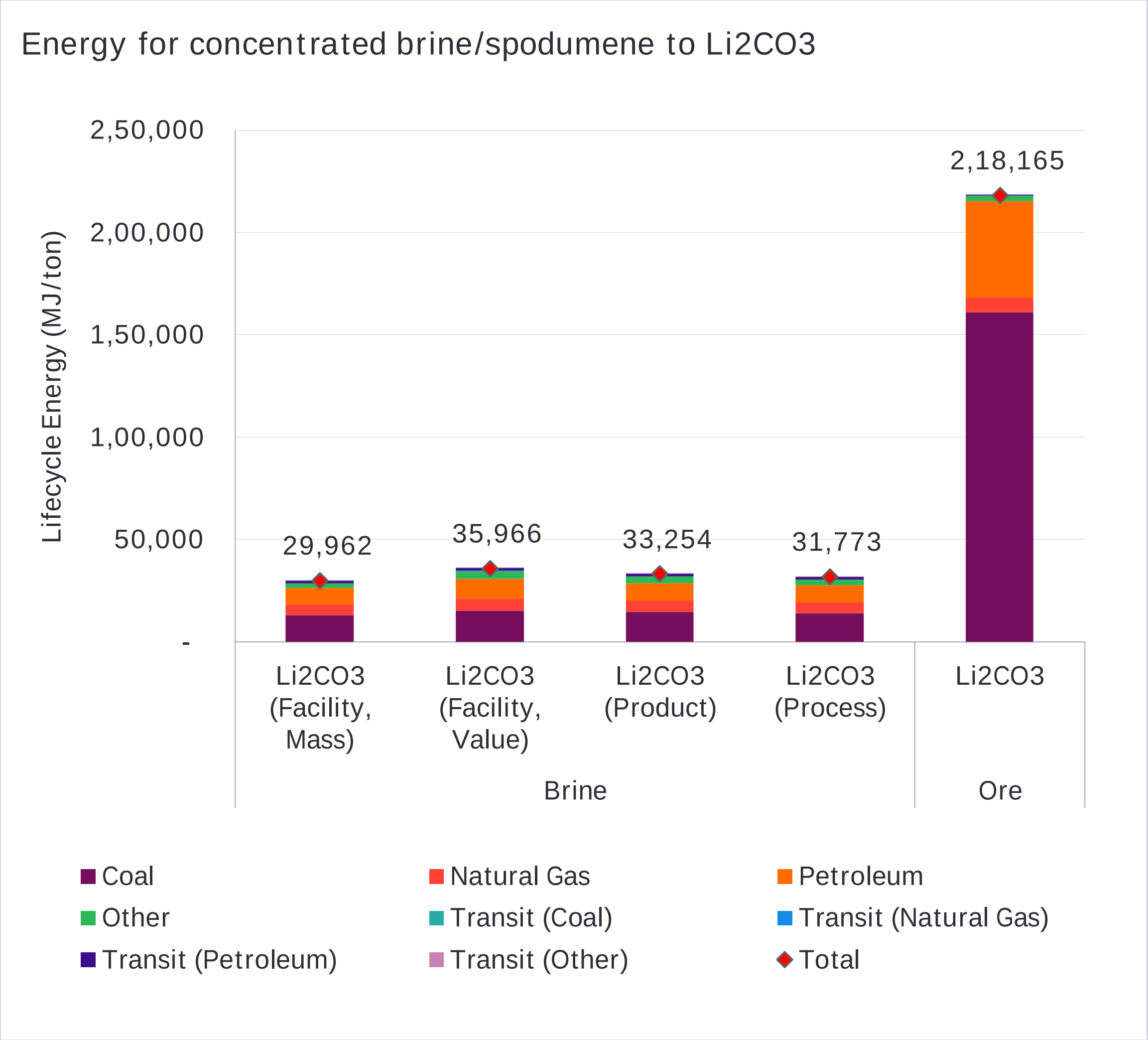
Energy consumption and GHG emissions during brine/spodumene concentration

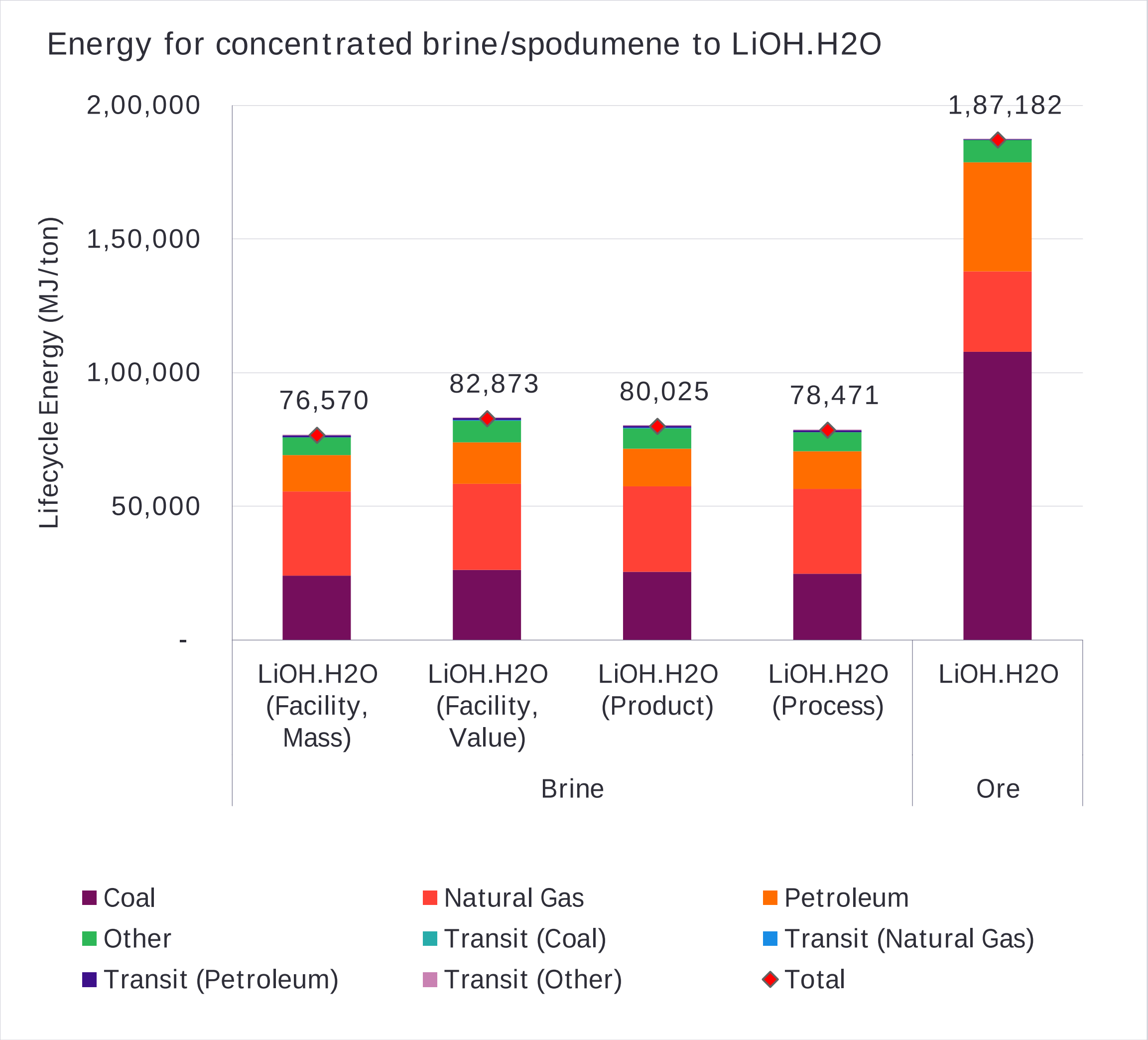




Source: Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries – ScienceDirect

Energy consumption during concentrated brine/spodumene to Li2CO3 /LiOH.H2O





Source: Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries – ScienceDirect

Global reserves of lithium: 59% of the reserves are in the top 10 and 75% in the top 20 mines

Mine	Company	List of owners	LOM	Production - 2020 (tons)
Mount Marion	Mineral Resources Limited	Ganfeng Lithium Co., Ltd. (Venturer) 50%; Mineral Resources Limited (Venturer) 50%	20	394000
Greenbushes	Tianqi Lithium Corporation	Albemarle Corporation (Venturer) 49%; Tianqi Lithium Corporation (Venturer) 26.01%; IGO Limited (Venturer) 24.99%	35	88000
Salar de Atacama	Sociedad Química y Minera de Chile S.A.	Sociedad Química y Minera de Chile S.A. (Owner) 100%		70000
Salar de Atacama	Albemarle Corporation	Albemarle Corporation (Owner) 100%	24	42000
Pilgangoora	Pilbara Minerals Limited	Pilbara Minerals Limited (Owner) 100%	15	13468
Silver Peak	Albemarle Corporation	Albemarle Corporation (Owner) 100%	33	2200
Altura	Pilbara Minerals Limited	Pilbara Minerals Limited (Owner) 100%	13	
Arcadia	Prospect Resources Limited	Prospect Resources Limited (Venturer) 87%; Private Interest (Venturer) 13%	18.3	
Bald Hill	Alita Resources Limited	Alita Resources Limited (Owner) 100%	3.6	
Bougouni	Kodal Minerals Plc	Kodal Minerals Plc (Owner) 100%; Private Interest (Fractional)	8.5	
Ewoyaa	Atlantic Lithium Limited	Atlantic Lithium Limited (Optionee) 100%; Merlink Resources Limited (Optionor); Obotan Minerals Ltd. (Optionor)	11.4	
Finniss	Core Lithium Ltd	Core Lithium Ltd (Owner) 100%	8	
Goulamina	Firefinch Limited	Firefinch Limited (Owner) 100%	21.5	
Grota do Cirilo	Sigma Lithium Corporation	Sigma Lithium Corporation (Owner) 100%	12.7	
Karibib	Lepidico Limited	Lepidico Limited (Venturer) 80%; Private Interest (Venturer) 20%	14	
Kathleen Valley	Liontown Resources Limited	Liontown Resources Limited (Owner) 100%; Ramelius Resources Limited (Fractional)	23	
Manono	AVZ Minerals Limited	AVZ Minerals Limited (Optionor) 51%; Congo (the Democratic Republic of the) (Venturer) 25%; Suzhou CATH Energy Technologies Co., Ltd. (Optionee) 24%	21	
Mt Cattlin	Allkem Limited	Allkem Limited (Owner) 100%	3.8	
Mt Holland - Lithium	Covalent Lithium Pty Ltd	Sociedad Química y Minera de Chile S.A. (Venturer) 50%; Wesfarmers Limited (Venturer) 50%	48	
Vulcan	Vulcan Energy Resources Limited	Vulcan Energy Resources Limited (Owner) 100%; Private Interest (Fractional)	30	
Zulu	Premier African Minerals Limited	Premier African Minerals Limited (Optionee) 100%; Private Interest (Optionor)	15	

Source: EY Analysis

🟨 Australia 🟦 Africa 🟩 South America 🟦 North America

S.No.	Mine	Reserves (kilo tons)
1	Uyuni Salt Flat	39,000.00
2	Salar de Atacama	19,604.24
3	Cauchari-Olaroz	9,938.00
4	Bonnie Claire	8,358.70
5	Lithium Nevada	7,321.00
6	Manono	6,640.00
7	Vulcan	6,415.05
8	Clayton Valley	5,961.79
9	Chaerhan Lake	5,600.00
10	McDermitt	4,080.40
11	Cuenca Centenario-Ratones	4,015.00
12	Greenbushes	3,716.33
13	Sonora	3,562.00
14	Pilgangoora	3,509.00
15	Salar del Rincon	3,371.10
16	Mariana	3,282.00
17	Cinovec	2,990.00
18	TLC	2,880.00
19	Mt Holland – Lithium	2,842.70
20	Alberta	2,830.61
21	Salar de Olaroz	2,605.00
22	Jadar	2,590.00
23	Sal de Vida	2,530.70
24	Salar de Cauchari	2,500.00
25	Pastos Grandes	2,361.00
26	Wodgina	2,200.00
27	Kathleen Valley	2,090.00
28	Salar del Hombre Muerto	1,800.00
29	Kachi	1,778.00
30	South-West Arkansas	1,753.00
31	Goulamina	1,570.00
32	Tres Quebradas	1,447.64
33	Pozuelos	1,436.43
34	Whabouchi	1,257.40
35	Candelas	1,193.90
36	All Others	16,990.75
	Total	192021.73

Global reserves of lithium: North America, South America and Europe

Mine	Company	List of owners	LOM
🟦 Alberta	E3 Metals Corp.	E3 Metals Corp. (Owner) 100%	20
🟦 Authier	Sayona Mining Limited	Sayona Mining Limited (Venturer) 75%; Piedmont Lithium Inc. (Venturer) 25%; Karora Resources Inc. (Fractional)	13.8
🟩 Candelas	Galan Lithium Limited	Galan Lithium Limited (Owner) 100%	40
🟩 Cauchari-Olaroz	Jujuy Energia y Mineria Sociedad del Estado	Ganfeng Lithium Co., Ltd. (Venturer) 46.66%; Lithium Americas Corp. (Venturer) 44.84%; Jujuy Energia y Mineria Sociedad del Estado (Venturer) 8.5%; Grupo Minero Los Boros S.A. (Fractional)	40
🟥 Cinovec	CEZ Group	CEZ Group (Venturer) 51%; European Metals Holdings Limited (Venturer) 49%	25
🟦 Clayton Valley	Cypress Development Corp.	Cypress Development Corp. (Owner) 100%; Unnamed Owner (Fractional)	40
🟦 Clayton Valley	Noram Lithium Corp.	Noram Lithium Corp. (Venturer) 75%; CDN Maverick Capital Corp. (Venturer) 25%	40
🟦 Clayton Valley	Schlumberger Limited	Schlumberger Limited (Optionee) 100%; Pure Energy Minerals Limited (Optionor)	20
🟦 Georgia Lake	Rock Tech Lithium Inc.	Rock Tech Lithium Inc. (Owner) 100%	11
🟩 Hombre Muerto North	Lithium South Development Corporation	Lithium South Development Corporation (Optionor) 70%; Sino Lithium Materials Pty Ltd (Optionee) 30%	30
🟦 James Bay	Allkem Limited	Allkem Limited (Owner) 100%	18.8
🟩 Kachi	Lake Resources NL	Lake Resources NL (Optionor) 75%; Lilac Solutions, Inc. (Optionee) 25%	25
🟥 Keliber	Sibanye Stillwater Limited	Private Interest (Venturer) 57.3%; Sibanye Stillwater Limited (Venturer) 30%; Nordic Mining ASA (Venturer) 12.7%	20
🟦 Lithium Nevada	Lithium Americas Corp.	Lithium Americas Corp. (Owner) 100%	46
🟩 Mariana	Ganfeng Lithium Co., Ltd.	Ganfeng Lithium Co., Ltd. (Owner) 100%	25
🟦 Maricunga	Minera Salar Blanco SpA	Lithium Power International Limited (Venturer) 51.55%; Minera Salar Blanco SpA (Venturer) 31.31%; Bearing Lithium Corp. (Venturer) 17.14%; Unnamed Owner (Fractional)	20
🟥 Mina do Barroso	Savannah Resources Plc	Savannah Resources Plc (Owner) 100%	11
🟦 Pakeagama Lake	Frontier Lithium Inc.	Frontier Lithium Inc. (Owner) 100%	26
🟦 Paradox	Anson Resources Limited	Anson Resources Limited (Owner) 100%; Unnamed Owner (Fractional)	20
🟦 Pastos Grandes	Lithium Americas Corp.	Lithium Americas Corp. (Owner) 100%	41
🟦 Piedmont	Piedmont Lithium Inc.	Piedmont Lithium Inc. (Owner) 100%	30

🟩 South America 🟦 North America 🟥 Europe

Global reserves of lithium: North America, South America and Europe

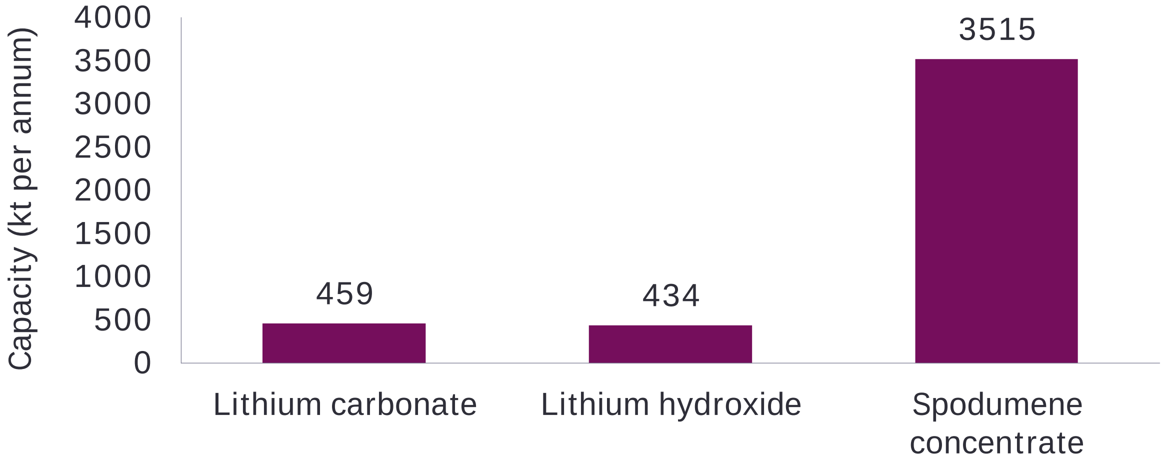
Mine	Company	List of owners	LOM
Pozuelos	Pluspetrol Resources Corporation B.V.	Pluspetrol Resources Corporation B.V. (Owner) 100%	20
Rhyolite Ridge	ioneer Ltd	ioneer Ltd (Owner) 100%	25.2
Rincon	Argosy Minerals Limited	Argosy Minerals Limited (Optionee) 90%; Private Interest (Optionor) 10%	16.5
Rose	Critical Elements Lithium Corporation	Critical Elements Lithium Corporation (Owner) 100%	17
Sal de Vida	Allkem Limited	Allkem Limited (Owner) 100%; POSCO Holdings Inc. (Fractional)	44
Salar de Cauchari	Allkem Limited	Allkem Limited (Venturer) 100%	30
Salar de Olaroz	Allkem Limited	Allkem Limited (Venturer) 66.5%; Toyota Tsusho Corporation (Venturer) 25%; Jujuy Energia y Mineria Sociedad del Estado (Venturer) 8.5%	20
Salar del Rincon	Rio Tinto Group	Rio Tinto Group (Owner) 100%	24.5
San Jose	Infinity Lithium Corporation Limited	Infinity Lithium Corporation Limited (Optionee) 100%; Beta Asociados, S.L. (Optionor); Disa Corporación Petrolífera, S.A. (Optionor); Grupo Empresarial Fuertes S.L. (Optionor)	26
Separation Rapids	Avalon Advanced Materials Inc.	Avalon Advanced Materials Inc. (Owner) 100%	19
Sonora	Bacanora Lithium Plc	Bacanora Lithium Plc (Venturer) 50%; Ganfeng Lithium Co., Ltd. (Venturer) 50%; Cadence Minerals Plc (Fractional)	19
South-West Arkansas	Standard Lithium Ltd.	Standard Lithium Ltd. (Optionee) 100%; TETRA Technologies, Inc. (Optionor)	20
Tres Quebradas	Zijin Mining Group Company Limited	Zijin Mining Group Company Limited (Owner) 100%	50
Whabouchi		Investissement Québec (Venturer); Orion Mine Finance (Dup) (Venturer); The Pallinghurst Group (Venturer)	33
Wolfsberg	European Lithium Limited	European Lithium Limited (Owner) 100%	12
Zinnwald	Zinnwald Lithium Plc	Zinnwald Lithium Plc (Owner) 100%	30

🟩 South America 🟦 North America 🟥 Europe

Source: EY Analysis

Capital projects of lithium extraction and processing under pipeline

Product – lithium carbonate	
Company – Product Development Stage	Expected capacity (ktPA)
Lithium Americas Corporation	249
Commissioning (2022)	60
Construction (2022)	80
Feasibility study (2022)	24
PEA study (2022)	85
Sociedad Quimica y Minera de Chile (SQM)	210
Expansion (2023)	210
Grand Total	459



Product – lithium hydroxide	
Company – Product Development Stage	Expected capacity (ktPA)
Albemarle Corporation	200
Production (2022)	200
IGO Limited	48
Train 1 – Production (2022)	24
Train 2 – Construction (2024)	24
Liontown Resources Limited	86
Production (2029)	86
Mineral Resources Limited	50
Production (2022)	50
Sociedad Quimica y Minera de Chile (SQM)	50
Expansion (2024)	50
Grand Total	434

Product – Spodumene concentrate	
Company – Product Development Stage	Expected capacity (ktPA)
AVZ Minerals Limited	700
Production (2023)	700
Core Lithium	175
Production (2023)	175
Liontown Resources Limited	700
Production (2024)	700
Mineral Resources Limited	750
Production (2023)	750
Pilbara Minerals	1,190
Commissioning (2022)	190
Expansion	1,000
Grand Total	3,515

Source: EY Analysis

Economics of converting spodumene concentrate to lithium hydroxide (~15,000 tons/annum)

COST CATEGORY	COST CODE	CAPITAL COST ESTIMATE (US$)
Direct	Equipment	47,933,932
Direct	Platework and Freight	7,190,089
Direct	Mechanical Installation	16,776,876
Direct	Civils	23,966,966
Direct	Structural Steel	9,586,786
Direct	Piping	16,776,876
Direct	Electrical	7,190,089
Direct	Control and Instrumentation	11,983,483
Direct	Non-Process - Facilities	7,190,089
Direct	Indirect Field Costs	44,578,557
Indirect	EPCM	37,148,797
Indirect	Owners Cost	11,887,615
Contingency	Contingency	60,552,540
Pre-production Mining Work	Pre-production Mining Work	50,257,185
	Total CAPEX	353,019,880

Production Capacity (tpa)	15,000
CAPEX (US$)	353,019,880
Life of operation (#years)	20
Total productionduring operation (ton)	300,000
CAPEX (US$/ton)	1,177
OPEX (US$/ton)	5,956
CAPEX+OPEX (USD/ton)	7,133

OPEX ITEM	US$/ton LiOH
Raw Materials	2,319
Logistics	114
Energy	614
Water	39
Reagents	834
Consumables	75
Labour	1,121
Maintenance	363
General and Admin	359
Waste Disposal	118
Sub Total	5,956
By-products	-
Total*	5,956

All-in sustaining costs include adjusted operating costs and sustaining capital expenditure, corporate general and administrative expenses, exploration expense, reflecting the full cost of production from current operations. The total all-in sustaining costs ranges from US$6,000 – US$12,000 per ton LCE in countries Argentina, Australia, Chile and China.

*Costs are during the year 2020

Source: Technical Report NI 43-101, Preliminary Economic Assessment, Canadian LiOH Project (minedocs.com)

Conditions for siting lithium carbonate / hydroxide conversion facilities

Ease of importing raw materials

India does not have any large deposits of lithium; the refinery would need to import raw materials from other countries. The location of the refinery should be close to ports or other transportation infrastructure to facilitate the import of raw materials. Road access for heavy haul vehicle from highway to the site industrial zone.

Access to resources

The location should have access to other resources, such as water and power, which are necessary for the refining process. The location should have simple access to the site for the future workforce.

Proximity to battery and electric vehicle industries

The Government of India has been actively promoting the development of the battery and electric vehicle industry, so the location of the refinery should be close to area where these industries are so that logistics cost of final product can be minimized.

Availability of subsidies

The cost of production will be a crucial factor as India does not have a large lithium deposit and the refining process will be heavily dependent on import of raw materials. So, the location should have favorable subsidies for setting up the refinery.

Environmental impact

The location should have minimal environmental impact and should be able to comply with all the environmental regulations and policies for refining of chemicals and disposal of industrial waste. The location should be far from residential areas.

Source: EY Analysis

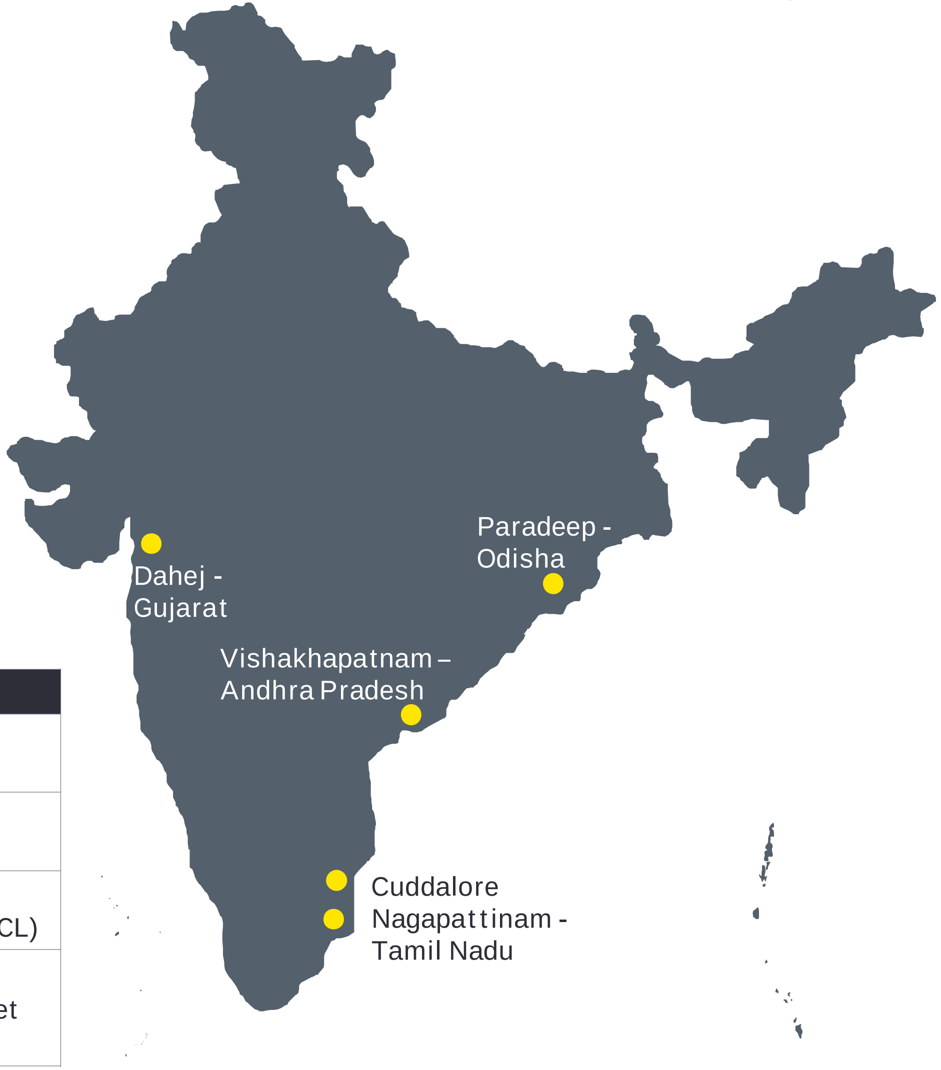
PCPIRs offer potential sites for investing and setting up lithium chemical refineries

The Petroleum, Chemicals and Petrochemicals Investment Region (PCPIR) policy by the Ministry of Chemicals and Petrochemicals, Govt. of India has been in existence since 2007. PCPIR is a designated investment region with an area of around 250 sq. km planned for the establishment of manufacturing facilities for domestic and export led production in petroleum, chemicals and petrochemicals, along with the associated services and infrastructure. The State Government plays the lead role in setting up of the PCPIR. It identifies a suitable site, prepares the proposal and seeks approval from a High-Powered Committee. State government is responsible for availability of reliable quality power, bulk requirements of water, road connectivity, Sewerage and effluent treatment linkages, from the edge of PCPIR to the final disposal sites. Key highlights of PCPIR policy:

- Strategic location at ports for domestic and global markets
- Availability of adequate land with Government agencies/developers
- Excellent connectivity, institutional mechanism for management and implementation
- Ready availability of technical and skilled personnel
- Investment opportunities in utilities and services

	Gujarat	Andhra Pradesh	Odisha	Tamil Nadu
Location/ Region	Dahej, Bharuch	Vishakhapatnam	Paradeep	Cuddalore-Nagapattinam
Total Area (Sq. kms.)	453	640	284	257
Anchor Tenant	ONGC Petro Additions Limited (OPaL)	Hindustan Petroleum Corporation Ltd. (HPCL)	Indian Oil Corporation Ltd. (IOCL)	Nagarjuna Oil Corporation Ltd. (NOCL)
Anchor Project Status	Commissioned in March 2017	Anchor Tenant for Greenfield project yet to come on board	Commissioned in February 2016	Construction work, stalled since 2011, yet to restart

Source: EY Analysis



Dahej in Gujarat, Barmer in Rajasthan and Yerpedu–Srikalahasti node in AP are well positioned to attract investors for setting up lithium refineries

The PCPIR in Dahej, Gujarat, has attracted more investments than the other three PCPIRs in India. The main reason behind more investments is clear long-term policy for investors, which facilitates ease of doing business. The state has undertaken various measures to enhance the "Ease of Doing Business" experience like implementation of Gujarat Single Window Clearance Act, 2017 which aims to facilitate a process for the speedy issuance of various licenses, clearances and certificates required for setting up a business unit. Gujarat MSME Act was also implemented in 2019 according to which an MSME in Gujarat can now start operation upon receipt of an acknowledgement certificate from the state nodal agency by submitting the 'Declaration of Intent' and without taking various approvals for the first three years. It has also formed an Investor Facilitation Agency (IFA) which operates at the state and district level for supporting prospective investors in the state. The state also provides Fixed Capital investment (FCI) to large industries for setting up manufacturing operations in the state in the form of capital subsidy without any upper ceiling. 10% and 12% of eligible FCI (excluding land) is provided for general and thrust sectors respectively without any upper ceiling in equal annual instalments of INR40 crore every year. The state had ~51% share (1st Rank in India) of IEMs filed in India in terms of value with a proposed investment of US$49 billion in 2019 as per the data released by DPIIT, Government of India.

Gujarat is ranked fifth in ease of doing business index by the Department of Industrial Policy and Promotion (DIPP). Andhra Pradesh, Odisha and Tamil Nadu ranks 1, 14 and 15 in the same index. Even after being ranked 1 in the ease of doing business index, Andhra Pradesh is not able to attract investments due to lack of poor power and water availabilities. Other challenges which are faced by these PCPIRs are:

- Elusive ROI: high financial risks with new projects and no attractive financial schemes
- Absence of utilities: lack of utilities like electricity, water, alternate energy, sewerage systems and ETPs
- Land acquisition and regulatory issues: slow pace of acquisition and limited government support, absence of a Single Window for approvals
- Lack of facilitative policy regime: no incentive to downstream industries because of high interest rates and lack of export incentives
- Feedstock for downstream: anchor tenant not sparing feedstock for downstream units

Rajasthan State Industrial Development and Investment Corporation Limited (RIICO) plans to develop a PCPIR in the vicinity of 9 MMTPA refinery cum petrochemical complex under construction by HPCL Rajasthan Refinery Limited (HRRL) at Pachpadra in the Barmer district. RIICO plans to complete the setup of a refinery complex by October 2023. The upcoming refinery is coupled with other regional advantages, such as:

- Within the influence region of the Delhi Mumbai Industrial Corridor (DMIC) and eight other corridors pass through the state
- Access to major ports – Kandla, Mundra, JNPT and numerous other ports along west coast
- Six-lane expressway running adjoining to the HRRL complex offering unhindered connectivity to Bhatinda and Jamnagar refineries for feedstock requirements and northern and western regions and ports for product evacuation
- Exemption for seven years from 100% of Electricity Duty, 100% Land Tax, 100% Market Fee
- Capital subsidy of 13–28% of eligible fixed capital investment available for manufacturing industries depending on the size of investment. Amount is to be disbursed in annual instalments in 10-year capital with cap of INR50 Cr in year 1 to 3, INR 65 Cr in year 4 to 7 and INR 80 Cr in year 8 to 10.

The Vishakhapatnam PCPIR faced public outcry over possible pollution to be caused by the petrochemical unit. So, to avoid the name PCPIR, it is being implemented as part of Vizag-Chennai Industrial Corridor (VCIC) funded by the Asian Development Bank. The region is announced to be developed as a mega petrochemical hub. VCIC is envisaged as a node centric development platform with four nodes, Visakhapatnam Node, Machilipatnam Node, Donakonda Node and Yerpedu - Srikalahasti Node. Amara Raja batteries have its manufacturing facility in Chittoor, which is around Yerpedu–Srikalahasti node. The corridor brings along the complementary components that include:

- A trade and transport corridor and long coastline and strategically located ports are expected to help India connect with dynamic Southeast and East Asia
- Urban centers along the corridor and production clusters producing goods for both consumption in the surrounding region and for global trade

Source: Industrial-Policy2020.pdf (gujarat.gov.in), https://ficci.in/spdocument/23084/White_Paper_on_PCPIR_Policy_Review.pdf, Reserve Bank of India - Publications (rbi.org.in), Rajasthan Investment Promotion Scheme 2022

International perspective: spherical graphite processing, bill of materials, reserves and assets

04

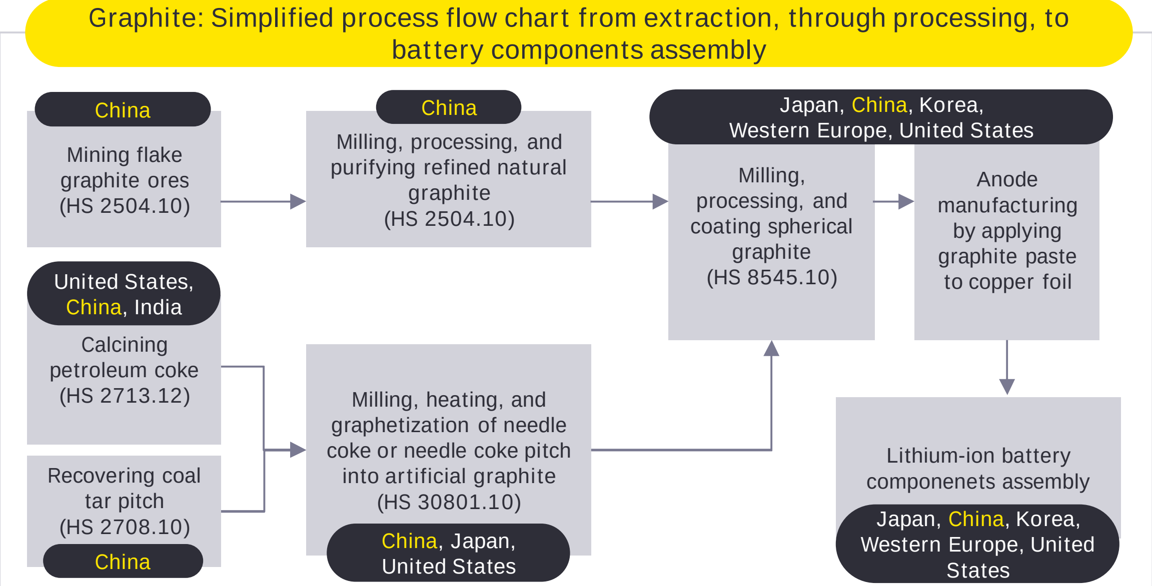
Overview: graphite refining process, reserves and mine production

Anodes for LIB cells are made of *spherical graphite* that involves processing/refining natural or synthetic graphite to have the right shape, particle size, and crystalline properties suitable for lithium intercalation chemistry.

Global output of mined graphite is highly concentrated with China accounting for almost three-fifths (59.1%) and the next four largest countries together exceeded one-quarter (26.9%) of the worldwide total in 2020. Reported global mine output of natural graphite steadily declined during 2015–20, with a notable dip in 2017. Some of the major suppliers of refined battery grade graphite are Hitachi Chemical, BTR New Energy, and Superior Graphite in the United States. The natural graphite must be properly heat-treated to obtain a high degree of graphite crystalline domains with exposed edge planes and surface treated (forming gas, nitric acid, and so on) to obtain the appropriate surface chemistry for solid electrolyte interphase (SEI) formation. Both oxygen-free surfaces and oxygen-rich surfaces can be beneficial for performance, depending on the electrolyte composition, cathode cell chemistry, and cycling conditions.

A lack of integration among raw and intermediate material producers characterizes the global value chain for artificial graphite, along with the lack of corporate participation by either battery manufacturers or EV manufacturers. Most of global production is petroleum-based rather than coal tar-based. Major producers of calcined petroleum coke are most in the United States, followed by China and India.

Graphite: Simplified process flow chart from extraction, through processing, to battery components assembly



China

Mining flake graphite ores (HS 2504.10)

China

Milling, processing, and purifying refined natural graphite (HS 2504.10)

Japan, China, Korea, Western Europe, United States

Milling, processing, and coating spherical graphite (HS 8545.10)

Anode manufacturing by applying graphite paste to copper foil

United States, China, India

Calcining petroleum coke (HS 2713.12)

Recovering coal tar pitch (HS 2708.10)

China

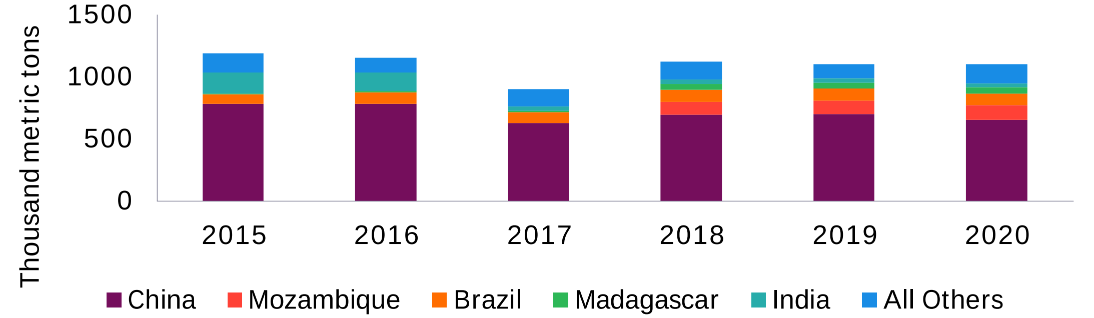
Milling, heating, and graphetization of needle coke or needle coke pitch into artificial graphite (HS 30801.10)

China, Japan, United States

Lithium-ion battery componenets assembly

Japan, China, Korea, Western Europe, United States

Mined Natural Graphite



Source: Global Value Chains: Graphite in Lithium-ion Batteries for Electric Vehicles gvc_paper.pdf (usitc.gov), https://www.usgs.gov/centers/nmic/graphite-statistics-and-information

Natural graphite to battery grade anode material processing

Graphite concentration

- Graphite ores (small flakes) extracted from either open-pit or underground operations are crushed and ground to get fine particles
- Flotation process is used to separate out the graphite from various impurities to attain a concentrate with a 90% to 97% graphite content

Purification, spheroidization and coating

- The remaining impurities (siliceous ash, sulfur, iron, and other metals) are removed either by wet-chemical leaching with strong acids or high-temperature electrical, thermal treatment with halogen gasses
- The concentrated graphite is dried and grinded to get uniform particles
- “Spheroidization” is done to get porous “micro-balls” (10–30 microns diameter) by heating in a kiln. The individual flakes curl into spheres to achieve increased packing density and reduced particle size for more efficient electrical conductivity
- This spheroidal graphite is subsequently coated with pitch or asphalt, followed by baking in a furnace to produce coated spheroidal graphite that prevents expansion and exfoliation of graphite

Natural graphite: Deposit types and characteristics

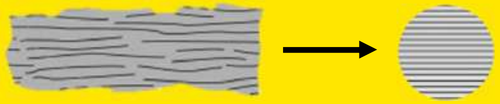
Description	Leading mine sources	Carbon content (%)	Advantages	Disadvantages
Flake – more common form, with visible flaky particles	Brazil, China, Mozambique	80–90	Low cost, and low impurities	Inconsistent quality
Amorphous– more common form, with small crystalline particles	China	70–90	Lowest cost	High impurities including ash
Crystalline-vein – least common form, with particle sizes ranging from fine flakes, medium needles, to grainy lumps	Sri Lanka	70-99+	Very high grades	Small deposits, underground, high cost, and small particles

Step 1: Mining and flotation

1. Mining from graphite ore
2. Mechanical separation
3. Flotation
4. Drying and screening

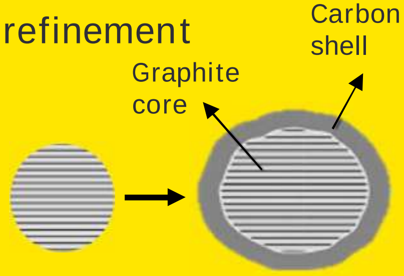
Step 2: Material Processing

1. Micronization
2. Spheroidization
3. Purification (wet chemical/thermal)



Step 3: Particle refinement

1. Conditioning
2. Grinding
3. Classifying
4. Coating



Source: Global Value Chains: Graphite in Lithium-ion Batteries for Electric Vehicles gvc_paper.pdf (usitc.gov), Performance and cost of materials for lithium-based rechargeable automotive batteries | Nature Energy

Synthetic graphite to battery grade anode material processing

Petroleum coke to calcined petroleum coke/needle coke

- Residual oil from petroleum refinery operations are roasted in a coking furnace to drive off the volatile components.
- The residual solid material is heated in a rotary kiln to burn-off the volatile residual water and organic compounds to yield calcined petroleum coke with a carbon content of 97.0% to 99.5%
- Only 5% of all petroleum coke produced meets the high-purity and structural requirements. These are known as needle coke.

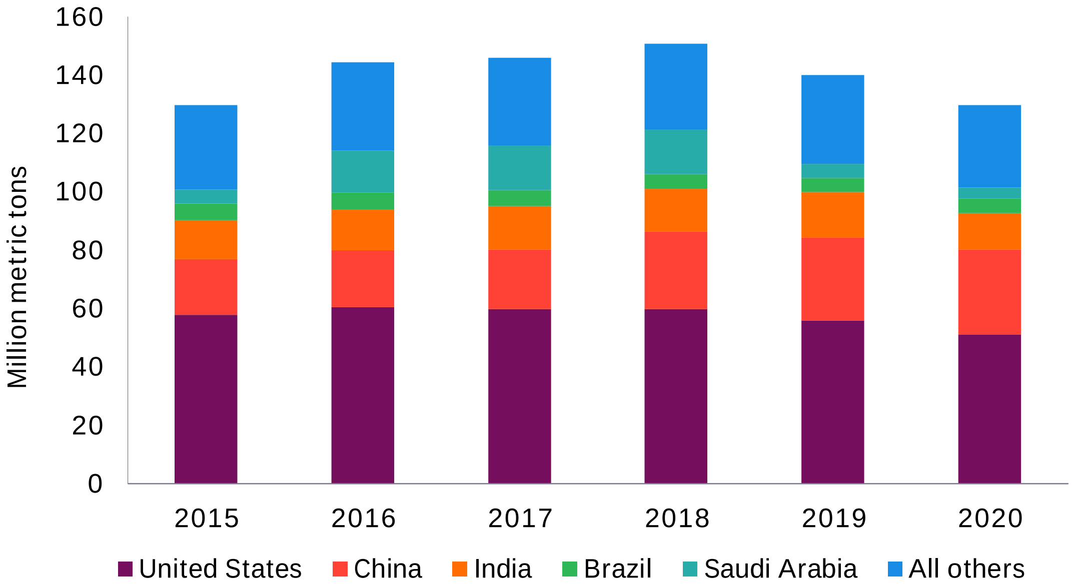
Coal tar to pitch coke

- Coal tar, a thick dark liquid obtained from coal coking operations, is transferred to another coking furnace to drive off the volatile components and yield solid coke.
- Distillation of this solid coke is done to remove water in the dehydration column, followed by removal of organic volatiles to yield coal tar pitch
- The coal tar pitch is heated in an electric furnace to bake the carbonaceous materials at 800–1,300 °C into fine-grained pitch coke

Graphitization

- The needle coke or pitch coke is heated in an electric furnace at higher temperatures in the range of 2,600 °C to 3,300 °C to crystallize the aligned carbonaceous materials into graphite

Petroleum Coke Producing Countries

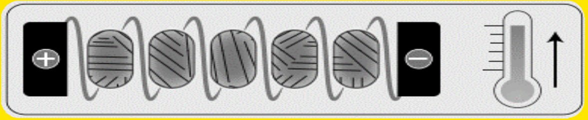


Step 1: Pre-treatment

1. Carbon precursor (coke/pitch)
2. Calcination: soft carbon
3. Crushing, grinding
4. Classifying

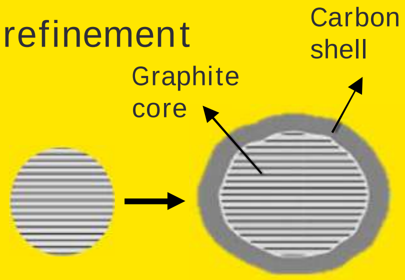
Step 2: Material Processing

1. Graphitization (>2,500˚C)



Step 3: Particle refinement

1. Conditioning
2. Grinding
3. Classifying
4. Coating

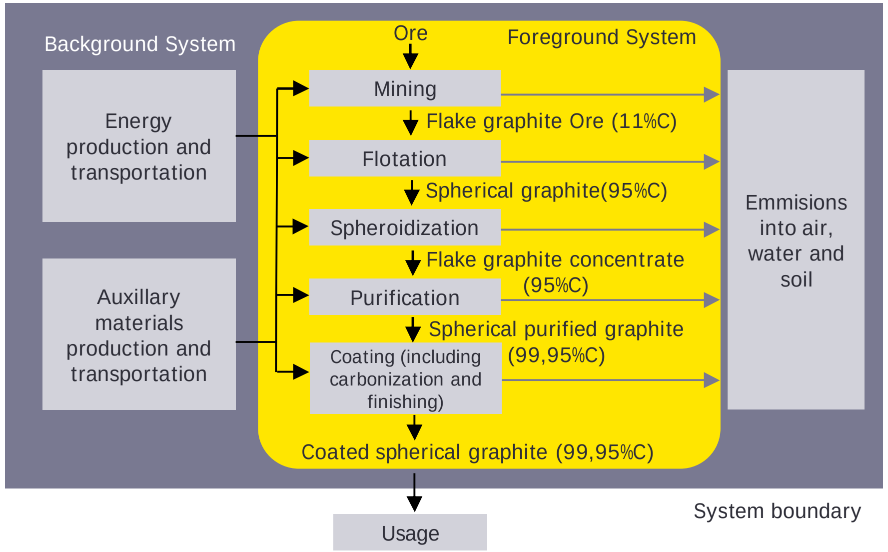


Source: Global Value Chains: Graphite in Lithium-ion Batteries for Electric Vehicles gvc_paper.pdf (usitc.gov), Performance and cost of materials for lithium-based rechargeable automotive batteries | Nature Energy, http://data.un.org/Data.aspx?d=EDATA&f=cmID%3APK

Life cycle inventory of materials for natural graphite processing to battery grade anode

Aggregated life cycle inventory for natural graphite production according to primary data collection at a Chinese manufacturer

Reference Product		Mining	Flotation	Spheronization	Purification	Coating	Unit
		Per 1t graphite ore	Per 1t graphite concentrate	Per 1t spherical graphite	Per 1t spherical purified graphite	Per 1t coated spherical graphite	
Input	Energy sources Electricity	8.7	506	2,100	305	4,550	kWh/t
	Diesel	2.241	0.996	0.415	0.249	0.249	kg/t
	Hard coal		50				kg/t
	Natural gas				1,050		MJ/t
	Material inputs						
	Graphite ore (11% C)		9,590				kg/t
	Graphite concentrate			2,220			kg/t
	Spherical graphite				1,130		kg/t
	Spherical purified graphite					1,010	kg/t
	Ammonium nitrate	0.248					kg/t
	Pine oil		1.163				kg/t
	Diesel	0.012	1.551				kg/t
	Ceramic grinding media		9				kg/t
	Hydrofluoric acid				180		kg/t
	Hydrochloric acid				200		kg/t
	Nitric acid				100		kg/t
	Water		22.027		25		m3/t
	Lime				400		kg/t
	HSP oil pitch					50.0	kg/t
	Nitrogen					1.5	kg/t
Output	By product						
	Graphite fines			1,215			kg/t
	Emissions to air						
	NOx	0.138					kg/t
	Graphite dust	5					kg/t
	Steam (H_2O)	0.113	320.145		320.145		kg/t
	Off gas (CO_2)	0.040	183.333		57.750	62.407	kg/t
	Nitrogen					1.5	kg/t
	Emissions to water						
	Pine oil		1.047				kg/t
	Diesel		1.396				kg/t
	Wastewater		21.707		24.773		m3/t
	Solid waste						
	Tailings		8,596				kg/t
	Industrial waste	0.025		0.25	917	45.5	kg/t



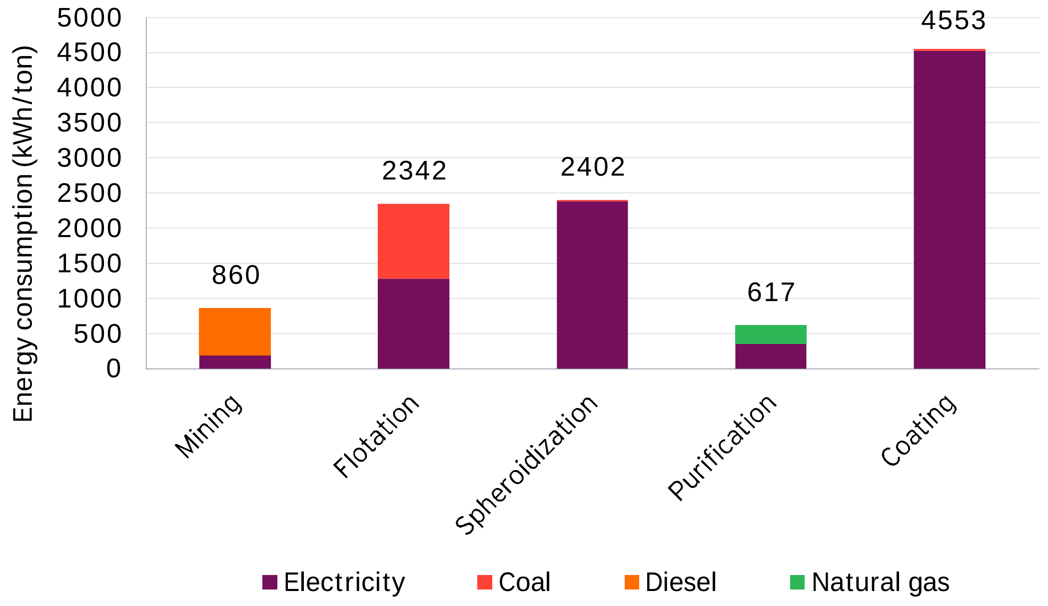
Material and Energy Inputs for the Production of 1 ton of Synthetic Graphite

	Carbonization	Carbon anode baking	Graphitization
Material inputs (ton/ton)			
Pet coke	0.95	0.99	---
Coal tar pitch	0.24	0.22	---
Energy inputs (MMBtu/ton)			
Residual oil	---	1.8	---
Diesel	---	0.33	---
Natural gas	5.1	2.4	---
Electricity	---	0.57	14
Total	5.1	5.2	14
Non-combustion Emissions (g/ton)			
NO_x	9,300	760	---
PM	4,100	320	---
SO_x	64,000	4,100	---
CO_2	440,000	150,000	---

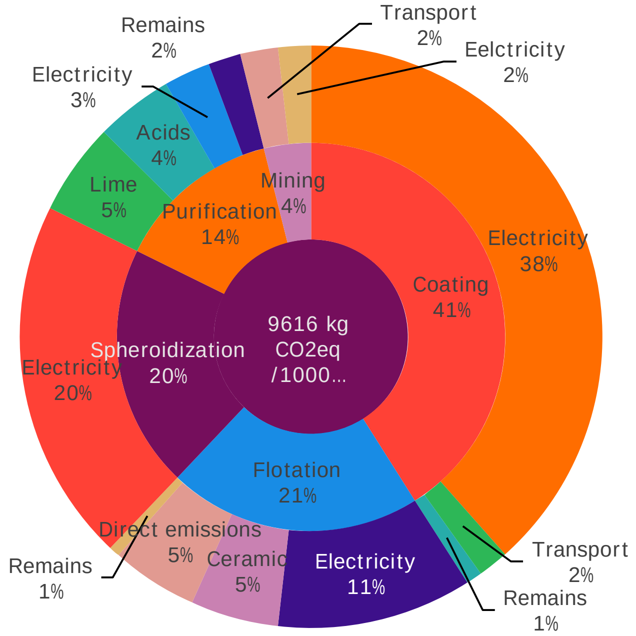
Source: Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data – ScienceDirect Material and energy flows in the production of cathode and anode materials for lithium ion batteries 121442.pdf (anl.gov)

Energy consumption and emissions while processing natural graphite into anode graphite

Energy consumption for each process step for 1 ton of produced anode graphite according to data from a Chinese graphite manufacturer



GHG emissions summary in battery grade graphite processing



- The largest electrical energy consumption takes place in the spheroidization step (~ 2,400 kWh) as well as in the coating step (~ 4,500 kWh)
- The least energy is required in the purification and mining process
- Hard coal plays a significant role as an energy carrier within the flotation step.

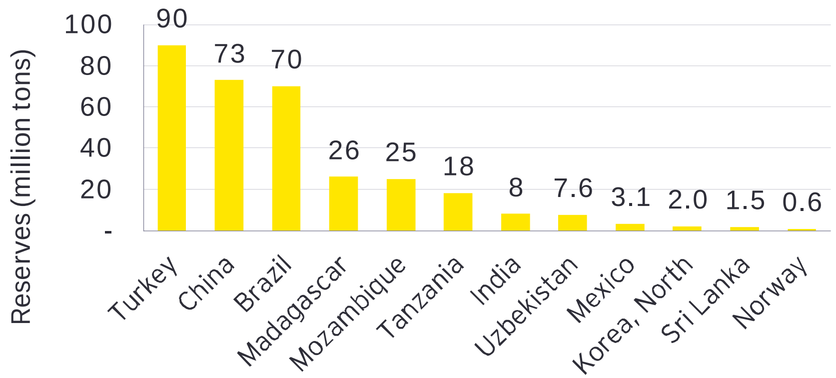
- The coating process is the key driver of GHG emissions with about 4000 kg CO2 eq. mainly associated with the electrical energy required for the process
- The second largest contributing process (2,000 kg CO2eq.) is the flotation process, due to the electrical energy required as well as the grinding media (ceramic) and direct CO2 emissions released in the process
- The main emission drivers in the purification process (~1,300 kg CO2eq.) are the acids used and the lime used for neutralization
- Overall, the mining process has a rather minor impact with ~380 kg CO2 eq.

Source: Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data - ScienceDirect

Global reserves and assets of natural graphite

Firm name (foreign headquarters location)	Mine location	State, province, region, county, etc.	Country
Extrativa Metaquimica S.A.	Maiquinique	Bahia State	Brazil
JMN Mineracao S.A.	Mateus Leme	Minas Gerais State	Brazil
Nacional de Grafite Ltda	Itapecerica, Pedra Azul, Salto da Divisa	Minas Gerais State	Brazil
Imerys Graphite and Carbon (Switzerland)	Saint Aime du Lac des Iles	Québec Province	Canada
Eagle Graphite Corp.	Black Crystal	British Columbia Province	Canada
Ontario Graphite Ltd.	Kearney	Ontario Province	Canada
Timcal Ltd.	Lac des Iles	Québec Province	Canada
Jixi Aoyu Graphite Co. Ltd.	Jixi, Luobei	Heilongjiang Province	China
Nei Mongol Xinghe Jingxin Graphite Co. Ltd.	Xinghe County	Nei Mongol Autonomous Region	China
Shenzhen BTR New Energy Materials Inc.	Changyuan	Heilongjiang Province	China
China Minmetals Corp.	Yushuan, Luobei County	Heilongjiang Province	China
Graphit Kropfmühl GmbH	Kropfmühl	Bavaria State	Germany
Agrawal Graphite Industries Ltd.	Belpara District	Odisha State	India
Tamil Nadu Minerals Ltd.	Sivaganga District	Tamil Nadu State	India
Yeongchon Graphite	Yeongchon	Hwangnam Province	North Korea
Etablissements Gallois S.A.	Artsirakambo Mine, Brickaville; Marovinsty Mine, Vatomandry; Ambalafotaka Mine, Toamasina	Atsinanana Province	Madagascar
Graphmada Equity Pte. Ltd. (Stratmin Global Resources plc., United Kingdom)	Antsirabe	Vakinankaratra Province	Madagascar
	Loharano	Arivonimamo Province	Madagascar
Grafitos Mexicanos, S.A. de C.V.	Lourdes, Topiyeca, San Juan	Sonora	State Mexico
GK Ancuabe Graphite Mine S.A. (Germany)	Ancuabe	Cabo Delgado Province	Mozambique
Syrah Resources Ltd. (Australia)	Balama	Cabo Delgado Province	Mozambique
Imreys Graphite and Carbon (Switzerland)	Otjiwarongo	Otjozondjupa Region	Namibia
Skaland Graphite AS (LNS Group)	Traelen Mine, Skaland	Troms County	Norway
Kahatagaha Graphite Lanka Ltd.	Kahatagaha Mine	Northwestern Province	Sri Lanka
Bogala Graphite Lanka Plc. (Germany)	Bogala Mine	Sabaragamuwa Province	Sri Lanka
Sakura Pvt. Ltd.	Ragedara Mine	Central Province	Sri Lanka
Leading Edge Materials Corp. (Canada)	Woxna	Gävleborg County	Sweden
Zavalyevskiy graphite complex	Zavalyevskiy	Autonomous Republic of Crimea	Ukraine
Zimbabwe German Graphite Mies Ltd.	Lynx Graphite Mine, Karoi	Mashonaland West Province	Zimbabwe

Natural graphite reserves



S. No.	Country	Reserves (million ton)	Percentage of total
1	Turkey	90	27.7%
2	China	73	22.5%
3	Brazil	70	21.6%
4	Madagascar	26	8.0%
5	Mozambique	25	7.7%
6	Tanzania	18	5.5%
7	India	8	2.5%
8	Uzbekistan	7.6	2.3%
9	Mexico	3.1	1.0%
10	Korea, North	2.0	0.6%
11	Sri Lanka	1.5	0.5%
12	Norway	0.6	0.2%
Total		325	100%

Source: EY Analysis, Global Value Chains: Graphite in Lithium-ion Batteries for Electric Vehicles gvc_paper.pdf (usitc.gov)

International perspective: nickel ore to battery market – pathways, reserves and assets

05

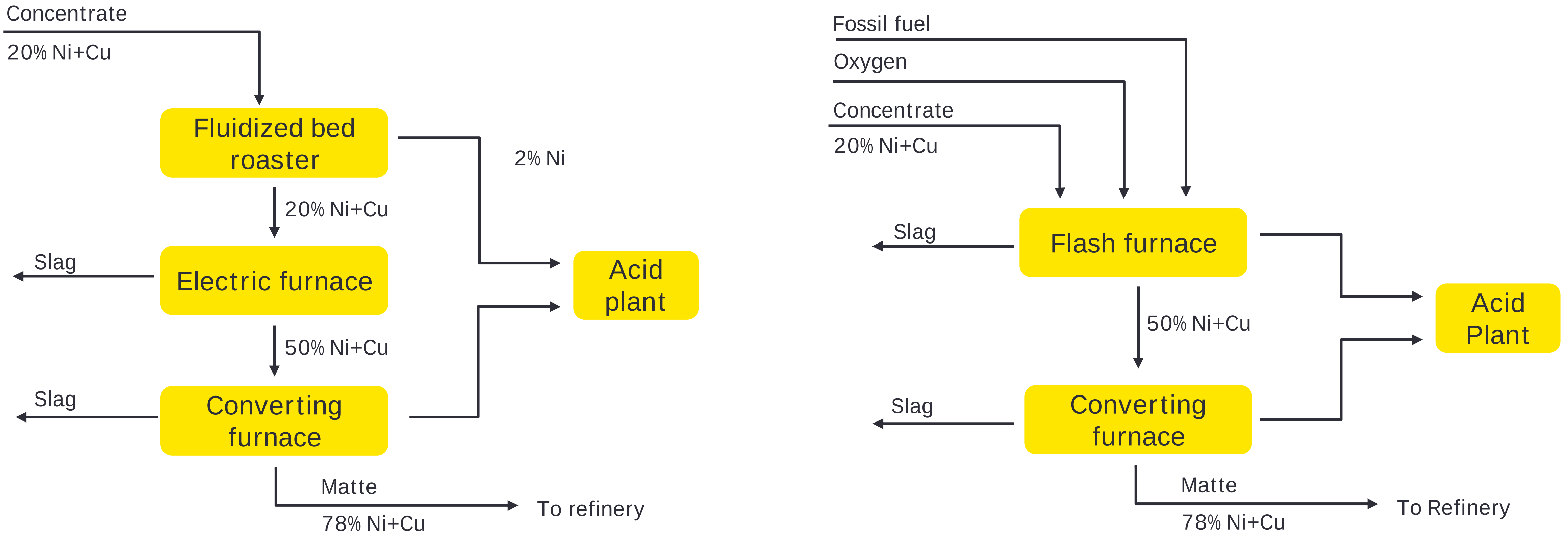
Nickel extraction processing, equipment and technologies

- Nickel is a naturally occurring metallic element with a silvery-white, shiny appearance. It is the fifth most common element on earth and occurs extensively in the earth's crust and core. The world's nickel resources are currently estimated at almost 300 million tons. Known nickel resources have significantly increased over the past 30 years, with a corresponding rise in nickel mine production. Australia, Indonesia, South Africa, Russia and Canada account for more than 50% of the global nickel resources. Economic concentrations of nickel occur in sulfide and in laterite-type ore deposits.
- While mine production in Canada and Russia is mainly linked to the mining of sulfide-type ore deposits, Indonesia and the Philippines predominantly mine laterites. In Australia, both laterite and sulfide mine production takes place. Due to their geological formation, laterite-type ore deposits and mines are principally found in equatorial regions and production from this type of deposits has steadily increased in recent decades.
- Nickel Class I describes a group of nickel products comprising electrolytic nickel, powders and briquettes, as well as carbonyl nickel.
- Nickel Class II comprises nickel pig iron and ferronickel. These nickel products commonly have a lower nickel content and are used especially in stainless steel production, where stainless steel producers take advantage of the iron content.
- Nickel is one of the most valuable common non-ferrous metals, along with aluminum, copper, lead and zinc (Al, Cu, Pb, Zn). Given its value as a commodity, the commercial motivation to use nickel effectively in the first place is very strong. There is a similarly compelling incentive for recovering and recycling nickel effectively at all stages of the production and use cycle.

	Nickel Sulfides	Nickel Laterites
Primary mineral	Pentlandite $Fe_5Ni_4S_8$	Garnierite $Ni_2Mg_4Si_4O_{10}(OH)_8$
Pre-concentration	5 to 10 X	Minimal
Associated pay metals	Copper, Cobalt, Gold, Silver, PGMs	Cobalt
Major impurities	Iron, Sulfur, Gangue (Rock)	Iron, Gangue
Processing options	Roaster - Electric Furnace Smelting Flash Furnace Smelting	Rotary Kiln - Electric Furnace Smelting
Smelting temperature	1300°C	1600°C
Energy source	Concentrate, Electricity	Fossil fuel, electricity
Primary product	Nickel Matte	Ferronickel (Class 2) 20 to 40% Ni
Final product post refining	High purity nickel cathode (Class 1) > 99.8% Ni, Plus by-products	N/A
Atmospheric emission	Sulfur Dioxide (SO_2)	Carbon Dioxide (CO_2)

Source: Life of Nickel by Nickel Institute

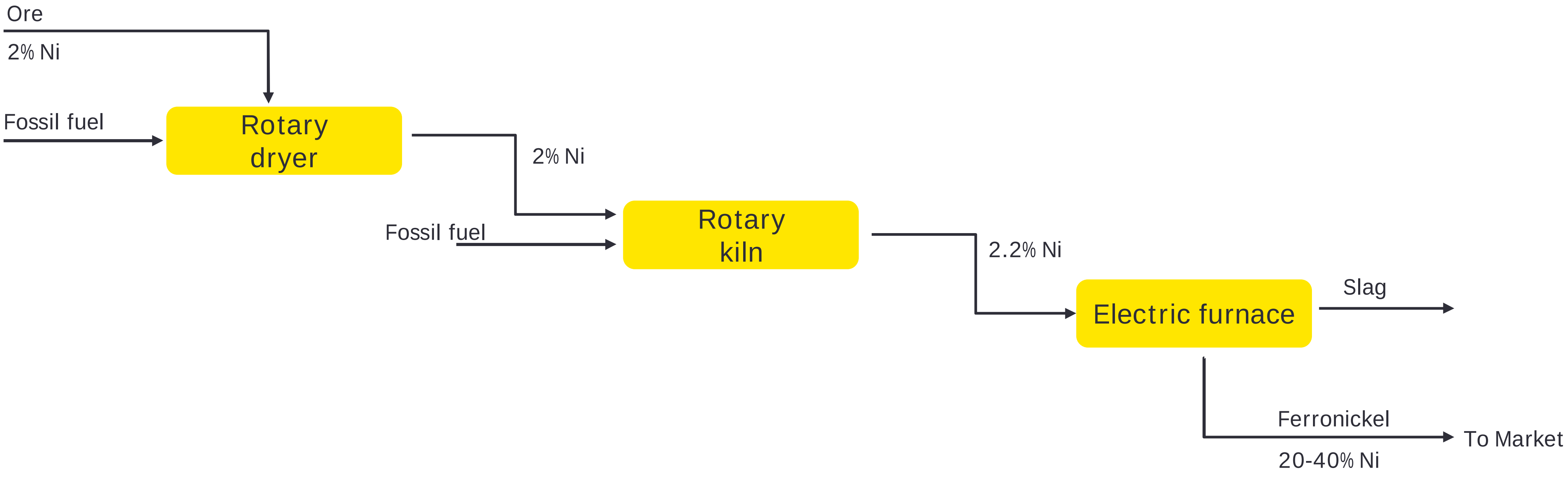
Nickel sulfide processing



	Roaster Electric Furnace	Flash Furnace
Primary energy consumption	25,000 kWh per ton Ni+Cu	500 kWh per ton Ni+Cu
Ni, Co recovery	98%, 75%	96%, 50%

Source: Glencore Nickel presentation dated May 2021

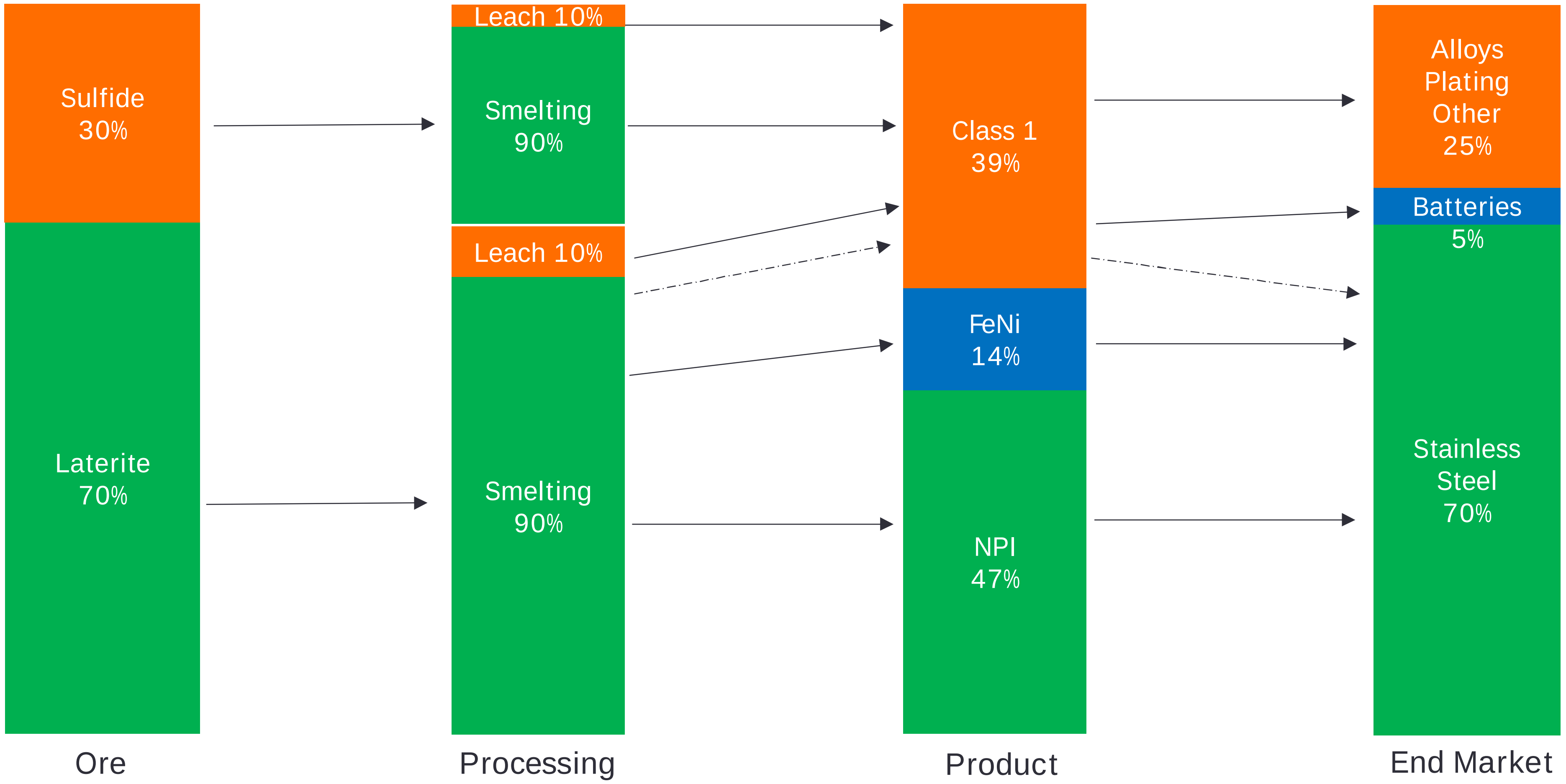
Nickel laterite processing



	Rotary Kiln – Electric Furnace (RKEF)
Primary energy consumption	20,000 kWh per ton Ni
Coal consumption	8 tons per ton Ni
Ni, Co recovery	92%, n/a

Source: Glencore Nickel presentation dated May 2021

Nickel ore to market pathways



Source: Glencore Nickel presentation dated May 2021

Nickel reserves, mines and assets

S.No.	Mine	Reserves (kilo ton)
1	Polar Division	15,299
2	NORI	11,512
3	TOML	9,954
4	Weda Bay	9,334
5	Dumont	5,721
6	Jinchuan	5,502
7	Turnagain	4,844
8	Hanking Group	4,802
9	Punta Gorda	4,093
10	Zebediela	4,010
11	Jacare	3,913
12	Terrafame	3,880
13	Biankouma-Sipilou	3,810
14	Koniambo	3,428
15	Kalgoorlie	3,189
16	Nickel West	3,136
17	Decar	3,111
18	Kola Division	3,066
19	Tapunopaka	2,940
20	Mindoro	2,926
21	Cerro Matoso	2,878
22	Crawford	2,874
23	Pomalaa East	2,690
24	Goro	2,633
25	La Sampala	2,624
26	All Others	96,973
	Total	219,142

Mine	Company	List of owners	LOM	Production - 2020 (ton)
Kola Division	Public Joint Stock Company Mining and Metallurgical Company Norilsk Nickel	Public Joint Stock Company Mining and Metallurgical Company Norilsk Nickel (Owner) 100%		172,357
Sudbury Operations	Glencore plc	Glencore plc (Owner) 100%		91,500
Nickel West	BHP Group Limited	BHP Group Limited (Owner) 100%		80,100
Sorowako	PT Vale Indonesia Tbk	PT Vale Indonesia Tbk (Owner) 100%		72,237
Ontario Division	Vale S.A.	Vale S.A. (Owner) 100%		43,200
Murrin Murrin	Glencore plc	Glencore plc (Owner) 100%		40,800
Cerro Matoso	South32 Limited	South32 Limited (Venturer) 99.94%; Mineworkers (Venturer) 0.06%		40,600
Voisey's Bay	Vale S.A.	Vale S.A. (Owner) 100%		35,700
Barro Alto	Anglo American plc	Anglo American plc (Owner) 100%		34,900
Koniambo	Glencore plc	Societe Miniere du Sud Pacifique SA (Venturer) 51% ; Glencore plc (Venturer) 49%		34,500
Ramu	Metallurgical Corporation of China Ltd.	Metallurgical Corporation of China Ltd. (Venturer) 56.97%; Jilin Jien Nickel Industry Co., Ltd. (Venturer) 11.05%; Jiuquan Iron and Steel (Group) Co., Ltd. (Venturer) 11.05%; Jinchuan Group International Resources Co. Ltd (Venturer) 5.93%; Mineral Resources Development Corp (Venturer) 3.94%; Private Interest (Venturer) 2.5%; Nickel 28 Capital Corp. (Carried) 8.56%		33,659
Moa Bay	Moa Nickel S.A.	General Nickel Co SA (Venturer) 50%; Sherritt International Corporation (Venturer) 50%		31,506
Goro	Prony Resources New Caledonia consortium	Prony Resources New Caledonia consortium (Venturer) 95% ; Societe de Participation Miniere du Sud Caledonia SAS (Venturer) 5%		31,000
Nova-Bollinger	IGO Limited	IGO Limited (Owner) 100%	10.3	30,436
Terrafame	Terrafame Oy	Terrafame Oy (Owner) 100%	22	28,740
Weda Bay	PT Weda Bay Nickel	Tsingshan Holding Group Co., Ltd. (Venturer) 51.3%; ERAMET S.A. (Venturer) 38.7%; PT Aneka Tambang Tbk (Venturer) 10%		23,500
Forrestania	Western Areas Limited	Western Areas Limited (Owner) 100%; Wesfarmers Limited (Fractional)		20,926
Eagle	Lundin Mining Corporation	Lundin Mining Corporation (Owner) 100%	3	16,718
Onca Puma	Vale S.A.	Vale S.A. (Owner) 100%	34	16,000
Ravensthorpe	First Quantum Minerals Ltd.	First Quantum Minerals Ltd. (Venturer) 70%; POSCO Holdings Inc. (Venturer) 30%		12,695
Kevitsa	Boliden AB (publ)	Boliden AB (publ) (Owner) 100%		11,074
Nkomati	African Rainbow Minerals Limited	African Rainbow Minerals Limited (Venturer) 50%; Public Joint Stock Company Mining and Metallurgical Company Norilsk Nickel (Venturer) 50%		10,638
Codemin	Anglo American plc	Anglo American plc (Owner) 100%		8,600
Trojan	Bindura Nickel Corporation Limited	Bindura Nickel Corporation Limited (Owner) 100%	5.4	5,730

Source: EY Analysis

Capital projects of nickel extraction and processing under pipeline

Company	Project	Product type	Project development stage	Expected capacity (TPA)	Capex (US$m)	Projected completion
Canada Nickel Company	Timmins Nickel District					
Glencore	Raglan phase 2 and Onaping depth projects		Commissioning			2,025
Nickel Mines Ltd.	Angel Ni project		Production			2,022
Nickel Mines Ltd.	Hengjaya mine					
Talon Metals Corp	Tamarack Nickel Project		Drilling			2,022
Vale	Bahodopi e Pomalaa			110,000		2,026
Vale	Onça Puma 2nd Furnace		Production	15,000		2,023
Vale	Thompson				121	
Vale	Voisey's Bay					
Nickel 28 Capital Corp.	Dumont Nickel-Cobalt Royalty	Ni and Co	Construction			
Nickel 28 Capital Corp.	Ramu Nickel Cobalt Operation	Ni and Co	Production			
Nickel 28 Capital Corp.	Turnagain Nickel and Cobalt Royalty	Ni and Co	Exploration			
Nickel 28 Capital Corp.	Flemington Nickel, Cobalt and Scandium Royalty	Ni, Co and Sc	Exploration			
Nickel 28 Capital Corp.	Nyngan Nickel, Cobalt and Scandium Royalty	Ni, Co and Sc	Construction			
Nickel Mines Ltd.	Oracle Ni project	Nickel metal		25,200		
Canada Nickel Company	Crawford project	Nickel sulfide	Feasibility study		1,200	2,022

Source: EY Analysis

06

International perspective: cobalt ore to battery market – pathways, reserves and assets

Cobalt minerology, refining, reserves and mine production

Cobalt is generally recovered as a by-product of copper or nickel mining. The major cobalt-producing regions are the Democratic Republic of Congo (DRC) and Zambia, with some large deposits also known in Australia, Russia, Cuba, New Caledonia and Canada. Cobalt can be found in economic concentrations in three principal deposit types:

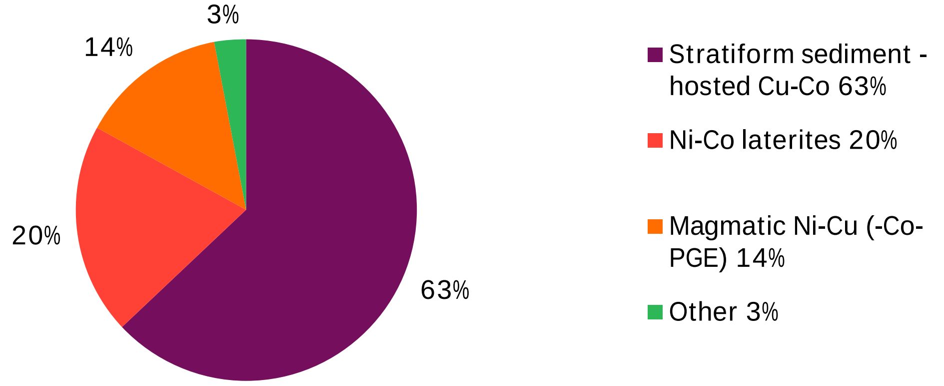
- Stratiform sediment-hosted copper-cobalt deposits
- Nickel-cobalt laterite deposits
- Magmatic nickel-copper (-cobalt-platinum-group element) sulfide deposits

Cobalt is also concentrated in a variety of other geological settings and deposit types. Some concentrations of cobalt may also occur on the sea floor in iron-manganese-rich nodules and cobalt-rich crusts, although to date no cobalt has been commercially extracted from these. The major cobalt-producing regions are the Democratic Republic of Congo (DRC) and Zambia, with some large deposits also known in Australia, Russia, Cuba, New Caledonia and Canada.

Cobalt is produced and traded in many forms, including concentrates, intermediate compounds, high-purity metal and salts. Pure cobalt metal is produced by two principal processing routes, hydrometallurgy and pyrometallurgy. Hydrometallurgy relies on differences in the solubility and electrochemical properties of different materials. Following leaching, copper is recovered, and impurities removed before the recovery of cobalt and, finally, of nickel, if any, is present. Pyrometallurgy uses differences in the melting points and densities of materials to separate them. The ore is heated together with a reducing agent to facilitate chemical reactions that separate the metals from other compounds. Some impurities are driven off in gaseous form and others are separated into a slag. After smelting, cobalt normally remains combined with nickel, and the two are subsequently separated using electrolytic processes (solvent extraction and electrowinning).

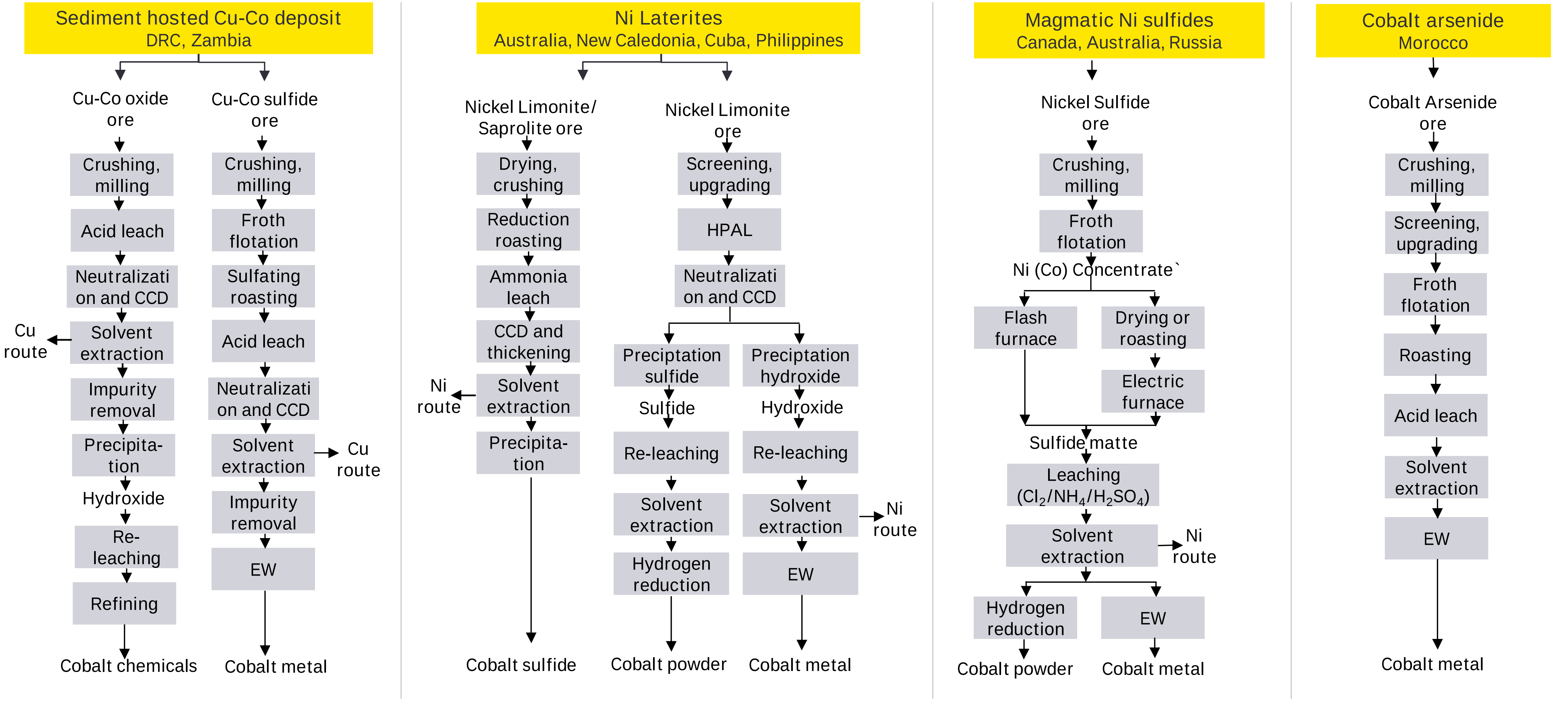
Country	Mine Production - 2021	% Production	Reserves (tons)	% Global Reserve
Congo (Kinshasa)	120,000	72.6%	3,500,000	45.8%
Russia	7,600	4.6%	250,000	3.3%
Other countries	6,600	4.0%	610,000	8.0%
Australia	5,600	3.4%	1,400,000	18.3%
Philippines	4,500	2.7%	260,000	3.4%
Canada	4,300	2.6%	220,000	2.9%
Cuba	3,900	2.4%	500,000	6.5%
Papua New Guinea	3,000	1.8%	47,000	0.6%
Madagascar	2,500	1.5%	100,000	1.3%
Morocco	2,300	1.4%	13,000	0.2%
China	2,200	1.3%	80,000	1.0%
Indonesia	2,100	1.3%	600,000	7.8%
United States	700	0.4%	69,000	0.9%
World total	165,300	100.0%	7,649,000	100.0%

Cobalt Mine Production by deposit type - 2017



Source: BGS COMMODITY REVIEW – Cobalt, Mineral Commodity Summaries 2022 - Cobalt (usgs.gov)

Refining cobalt ore to pure metal and battery grade chemical precursors



Sediment hosted Cu-Co deposit
DRC, Zambia

Cu-Co oxide ore
Crushing, milling
Acid leach
Neutralization and CCD
Solvent extraction → Cu route
Impurity removal
Precipitation
Hydroxide
Re-leaching
Refining
Cobalt chemicals

Cu-Co sulfide ore
Crushing, milling
Froth flotation
Sulfating roasting
Acid leach
Neutralization and CCD
Solvent extraction → Cu route
Impurity removal
EW
Cobalt metal

Ni Laterites
Australia, New Caledonia, Cuba, Philippines

Nickel Limonite/ Saprolite ore
Drying, crushing
Reduction roasting
Ammonia leach
CCD and thickening
Solvent extraction → Ni route
Precipitation
Cobalt sulfide

Nickel Limonite ore
Screening, upgrading
HPAL
Neutralization and CCD

Preciptation sulfide
Sulfide
Re-leaching
Solvent extraction
Hydrogen reduction
Cobalt powder

Preciptation hydroxide
Hydroxide
Re-leaching
Solvent extraction → Ni route
EW
Cobalt metal

Magmatic Ni sulfides
Canada, Australia, Russia

Nickel Sulfide ore
Crushing, milling
Froth flotation
Ni (Co) Concentrate`
Flash furnace
Drying or roasting
Electric furnace
Sulfide matte
Leaching ($Cl_2/NH_4/H_2SO_4$)
Solvent extraction → Ni route
Hydrogen reduction
Cobalt powder
EW
Cobalt metal

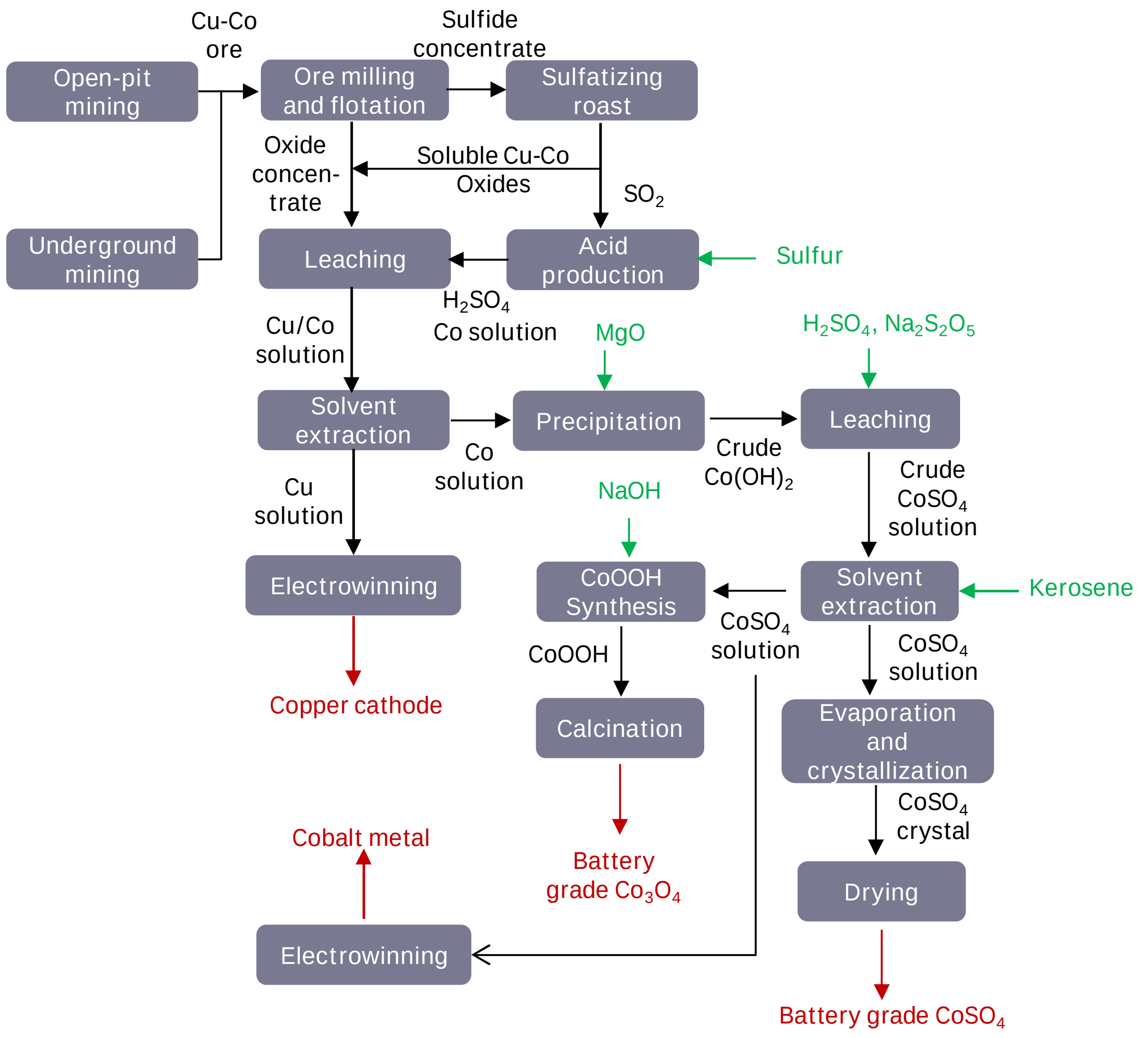
Cobalt arsenide
Morocco

Cobalt Arsenide ore
Crushing, milling
Screening, upgrading
Froth flotation
Roasting
Acid leach
Solvent extraction
EW
Cobalt metal

Source: Geometallurgy of cobalt ores: A review - ScienceDirect

CCD: Counter Current Decanation, EW: Electrowinning, HPAL: High Pressure Acid Leaching

Refining process of Cu-Co oxide and sulfide ore to battery grade cobalt



Source: https://greet.es.anl.gov/files/update_cobalt

Hydrometallurgical Processing

- Milling is done which reduces the ore size to one that is suitable for subsequent mineral extraction and leaching processes. The ore is converted into an enriched concentrate by flotation.
- Concentrate containing sulfides undergo sulfating roasting or pressure oxidation, which converts sulfides into more soluble oxides. Then the concentrate can be fed to the leaching tank. Concentrate containing oxides can be directly fed to the leaching tank.
- The leached slurry then undergoes several solvent extraction and stripping steps to increase the concentrations of copper and cobalt and separate them out as a copper-rich solution and a cobalt-rich solution.
- The cobalt-rich solution goes through a few precipitation steps to remove iron, aluminum, and manganese impurities, and to recover contained copper.
- In the end, magnesium oxide (MgO) is used to precipitate $Co(OH)_2$ with ~35% cobalt content.

Battery Grade $CoSO_4$ production

- $Co(OH)_2$ is treated with H_2SO_4, which leaches cobalt out as $CoSO_4$. Sodium metabisulfite ($Na_2S_2O_5$) is also added to the leaching step to convert the remaining Co^{3+} into Co^{2+}.
- The leached solution undergoes several precipitation steps to remove iron and aluminum. Solvent extraction by P-204 to remove other impurities, another solvent extraction by P-207 to separate cobalt from nickel, stripping by sulfuric acid to produce refined $CoSO_4$.
- Finally, the solution is evaporated, followed by filtration and drying to produce battery-grade $CoSO_4$ crystals

Battery Grade Co_3O_4 production

- Refined $CoSO_4$ reacts with ammonium bicarbonate (NH_4HCO_3) to produce a $CoCO_3$ slurry
- The produced $CoCO_3$ slurry goes through centrifugation, filtration, and washing to produce a concentrated $CoCO_3$ solution.
- The solution subsequently undergoes evaporation, drying, and an iron-removal step, to produce a refined $CoCO_3$ solid
- The solid is then calcined to produce battery-grade Co_3O_4 powder

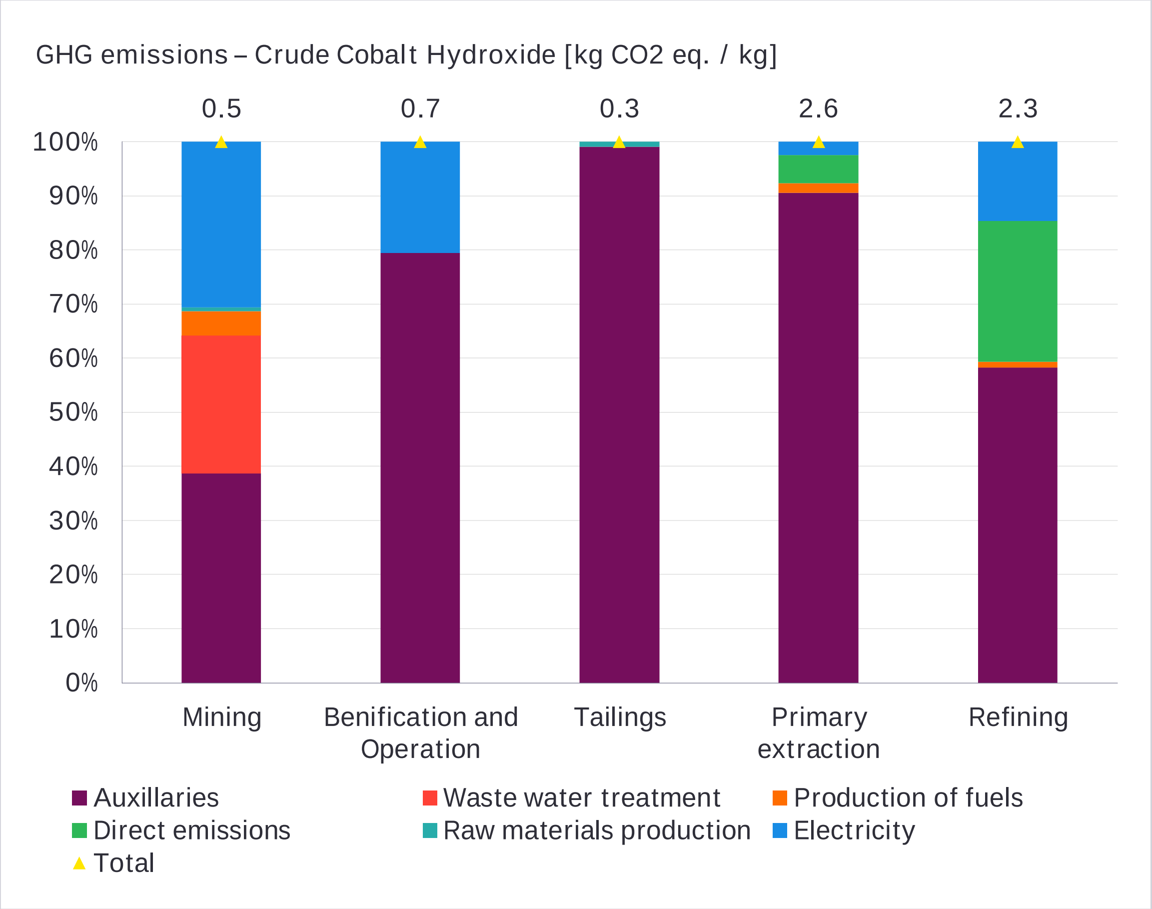
Life cycle inventory of materials and energy consumption for cobalt processing

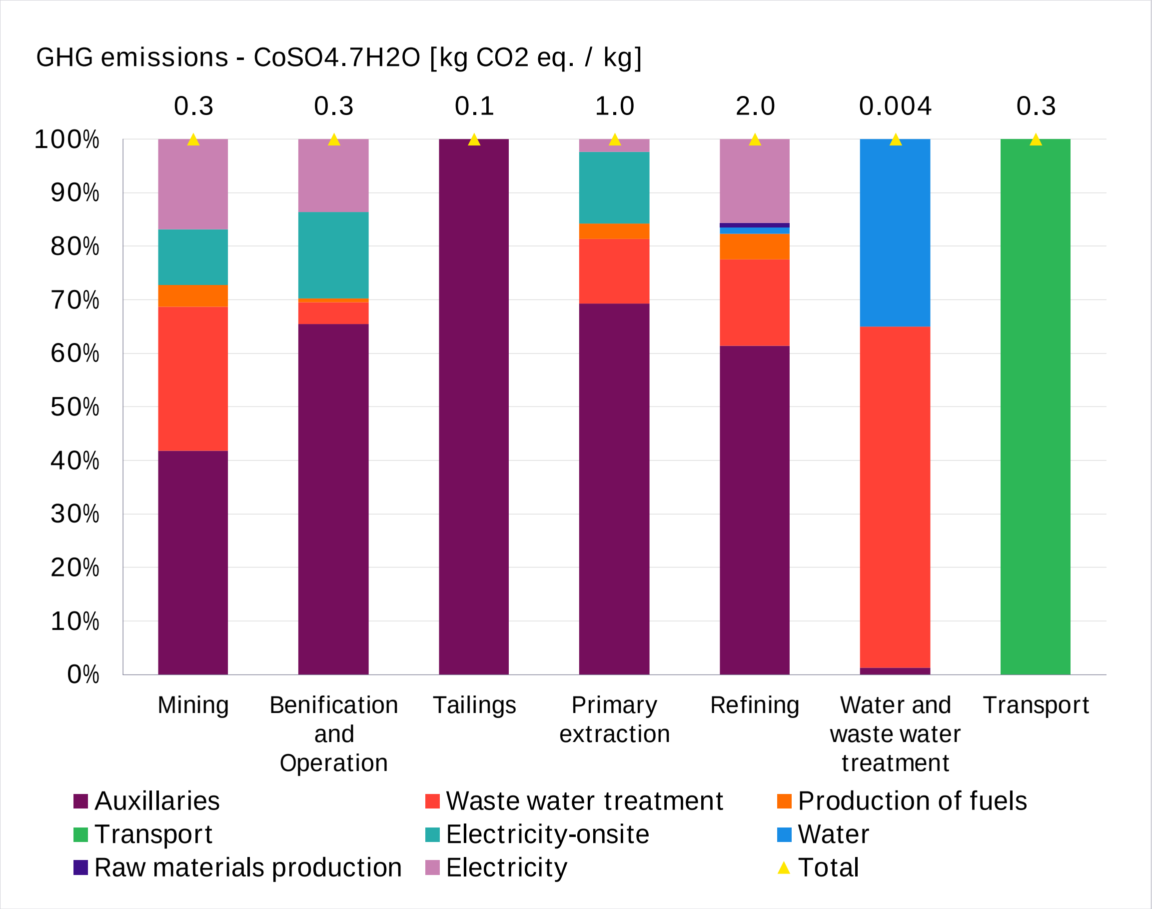
	Mass allocation		Economic value allocation		$CoSO_4$ production	Co_3O_4 production	Co electrowinning
	Mining	Ore processing	Mining	Ore processing			
Material consumption							
Sulfur (ton/ton)	---	0.721	---	3.153	---	---	---
Limestone (ton/ton)	---	0.938	---	4.102	0.056	---	---
Lime (ton/ton)	---	0.342	---	1.494	0.022	---	---
NaOH (ton/ton)	---	0.041	---	0.180	2.735	0.640	---
MgO (ton/ton)	---	1.175	---	1.175	---	---	---
H_2SO_4 (ton/ton)	---	---	---	---	2.570	---	---
HCl (ton/ton)	---	---	---	---	1.409	---	---
Kerosene (ton/ton)	---	---	---	---	0.047	---	---
$Na_2S_2O_5$ (ton/ton)	---	---	---	---	0.080	---	---
NH_4HCO_3 (ton/ton)	---	---	---	---	0.574	1.850	---
Na_2CO_3 (ton/ton)	---	---	---	---	0.088	---	---
Non-fuel-combustion process emissions							
PM10 (g/ton)	55,849	---	183,592	---	---	---	---
PM2.5(g/ton)	5,764	---	18,949	---	---	---	---
SO_2 (g/ton)	---	6,575	---	28,760	---	---	---
CO_2 (g/ton)					---	680,400	---
Energy consumption							
Diesel (MJ/ton)	22,757	---	74,809	---	---	---	---
Electricity (MJ/ton)	---	7,075	---	30,946	10,909	112	11,104
Natural gas (MJ/ton)	---		---	---	28,314	19,511	---
Water consumption							
Fresh water (m^3/ton)	6.66	34.06	21.90	148.98	49.56	12.44	---

Source: https://greet.es.anl.gov/files/update_cobalt

Global warming potential of different stages of Co(OH)2 and CoSO4 production

Electricity usage and direct emissions (e.g., diesel usage) are known impacts particularly for Global Warming Potential (GWP). Auxiliaries (i.e., chemicals) contribute significantly for the emissions. It is notable that transportation, though a very visible impact in global value chains, accounts for between 7.5% of the total product GWP.



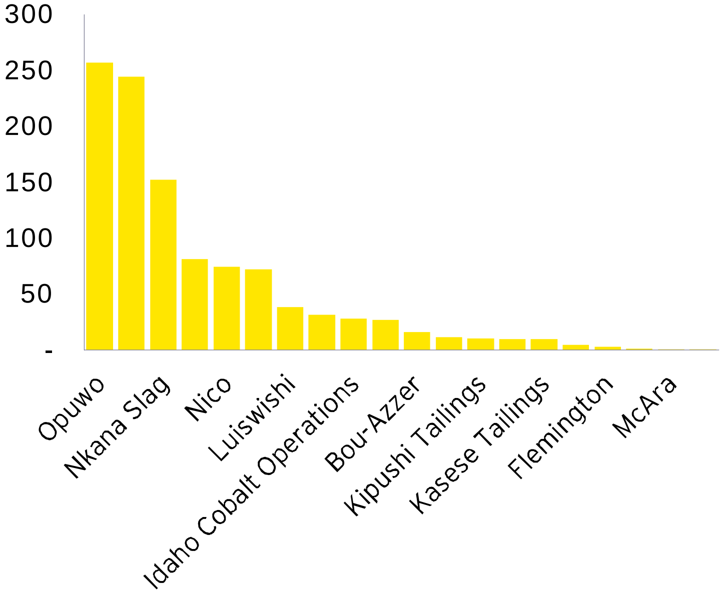


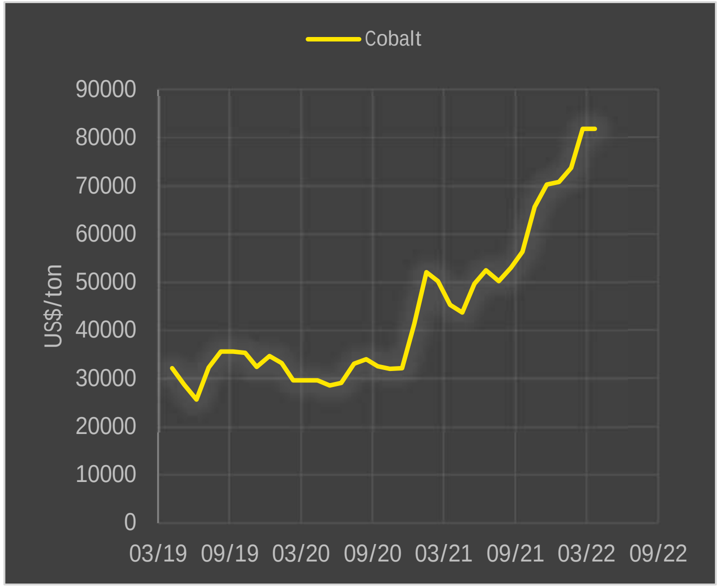
Source: Life Cycle Assessment - Cobalt Institute

Reserves and assets of cobalt, price history of cobalt

S.No.	Mine	Reserves (kt)	Percentage (%)
1	Opuwo	257	24.00%
2	Boss	244	22.80%
3	Nkana Slag	152	14.20%
4	Thackaringa	81	7.60%
5	Nico	74	6.90%
6	SCONI	72	6.70%
7	Luiswishi	38	3.60%
8	Mt Thirsty	32	3.00%
9	Idaho Cobalt Operations	28	2.60%
10	Norseman	27	2.50%
11	Bou-Azzer	16	1.50%
12	Iron Creek	11.3	1.10%
13	Kipushi Tailings	10.4	1.00%
14	Kambove	9.4	0.90%
15	Kasese Tailings	9.4	0.90%
16	Coronation Dam	4.3	0.40%
17	Flemington	2.7	0.30%
18	Wollogorang	1.2	0.10%
19	McAra	0.6	0.10%
20	Werner Lake	0.3	0.00%

Cobalt Reserves (kilo ton)





Mine	Company	List of owners	LOM	Production - 2020 (t)
Bou-Azzer	Compagnie de Tifnout Tighanimine	Managem S.A. (Owner) 99.79%; Unnamed Owner (Owner) 0.21%		2,416
Idaho Cobalt Operations	Jervois Global Limited	Jervois Global Limited (Owner) 100%	7	
Mt Thirsty	Conico Ltd.	Conico Ltd (Venturer) 50%; Greenstone Resources Limited (Venturer) 50%	12	
Thackaringa	Cobalt Blue Holdings Limited	Cobalt Blue Holdings Limited (Owner) 100%	17	
Flemington	Australian Mines Limited	Australian Mines Limited (Owner) 100%	18	
Nico	Fortune Minerals Limited	Fortune Minerals Limited (Owner) 100%	20	
SCONI	Australian Mines Limited	Australian Mines Limited (Owner) 100%	30	

Source: EY Analysis

Capital projects under pipeline

Company	Project	Product type	Project development stage	Expected capacity (TPA)	Capex (US$m)	Projected completion	Project details
Glencore							Production step-up from 2022 in line with the ramp-up of Mutanda (to c.10kt p.a. over the outlook period) and higher volumes from the Katanga cobalt circuit
Polymet Mining Corp.	NorthMet project	Cobalt concentrate and hydroxide			1,204		Phase I: produce and market copper and nickel concentrates
							Phase II: production of nickel- cobalt hydroxide, and precious metals precipitate products
Vale	Voisey's Bay	Cobalt deposit					Open pit mine nearing the end. Underground mining to develop two new ore bodies, extending to 2034. Signed deal in 2018 worth $690 million for sale of by product cobalt with Wheaton Precious Metals Corp and Cobalt 27 Capital Corp
Electra Battery Minerals	Battery Materials Park - Cobalt Refinery	Battery grade cobalt	Construction	6,500		2,025	Phase 1 - Funded US$67m capital for commissioning in Dec'22. Operate refinery in North America with 50 tons per day (tpd) $Co(OH)_2$ feed from Glencore and IXM; Ramping up to 6,500t battery grade cobalt per year
							Phase 2 - Recycling demonstration plant with the investment of US$3m. Work commenced to commission lithium -ion battery recycling line in 2023 in Ontario, Canada.
							Phase 3, Nickel sulfate plant, initially producing in excess of 60,000 tons of nickel.
							phase 4, replicate in Finland, South Korea and China, catering to a rapidly expanding battery cell industry in the U.S. and Canada.
China Molybdenum	KFM copper and cobalt mine in DRC	Cobalt deposit	Drilling				Exploration work during 2021. A total of 14 drilling holes were completed with a total drilling footage of 4,937.5 meters.
China Molybdenum	TFM copper and cobalt mine in DRC	Cobalt deposit	Drilling				Exploration activities in 2021 around the copper and cobalt and limestone deposit. Geological exploration activities carried out in DDPN, Pumpi west, Kamalondo south, Fungurume Hill, Kansalawile south, Mambilima and Mofya
Electra Battery Minerals	Iron Creek project	Cobalt deposit	Drilling				Completed 2,500-metre drill program in 2021, targeting extensions to the resource along strike to the cobalt-rich east and copper-rich west. Increase the resource size at Iron Creek and advance the asset towards a development decision in next 2 years
Sherritt International	Moa - slurry prep plant	Mixed sulfides	Production	1,700	27	2,024	Slurry Prep Plant - increased mixed sulfides feed for refinery; reduced ore haulage distances; reduced carbon intensity; underpins expansion with the capacity of 1,700 tons of increased mixed sulfides production. Total budget within US$20k to US$25k per ton of increased nickel capacity.
Sherritt International	Fort Saskatchewan refinery	Refined metal	Debottlenecking				Current annual capacity of ~35,000 (100% basis) tons of nickel and ~3,800 (100% basis) tons of cobalt. Debottlenecking at Fort site - upgrade/expand equipment to increase total refined metal output capacity to ~41,000 tpa.

Source: EY Analysis

Strategies and action plan for supporting domestic value addition

07

Strategies for critical battery mineral supply chain resilience – status quo review

Strategic intervention	Lithium	Nickel	Cobalt	Graphite
Domestic exploration, mining and refining of critical battery minerals	• Preliminary exploration (G3) in the Salal-Haimana area of Reasi District of Jammu and Kashmir (UT) has indicated ~5.9 million tons of mineral bearing resources in the inferred category • Lack of mining and refining capacity necessitates reliance on imports	• ~189 million tons of mineral bearing resources estimated in Odisha, Jharkhand and Nagaland • Lack of mining and limited refining capacity for battery grade nickel precursor necessitates reliance on imports	• ~45 million tons of estimated mineral bearing resources in Odisha, Jharkhand and Nagaland • Limited refining capacity necessitates reliance on imports	• Graphite deposits of economic importance and active mining centers are in Jharkhand, Odisha and Tamil Nadu • Spherical graphite refining capacity is negligible and therefore necessitates reliance on imports • Private sector announcements to manufacture spherical graphite may reduce import reliance in future
Overseas exploration and mining of critical battery minerals	• G2G dialogues are advancing with friendly countries (e.g., Australia, Chile, Argentina, Bolivia etc.) for joint exploration and mining; Government of India has set up KABIL to ensure a consistent supply of critical and strategic minerals through G2G negotiations and acquiring mining assets abroad			
Establish supply chain linkages with friendly foreign countries	• G2G dialogues are advancing for setting up 'Critical Minerals Security Partnership (CMSP)' among G20 member countries and also within the Indo-Pacific economic framework			
R&D to develop recycling, extraction technologies and find earth abundant alternatives to critical battery minerals	• A private sector start up based in Noida has established recycling technology with commercialized products and services • DST has supported 42 projects to disseminate the knowledge of advancement in future energy materials - aluminum ion batteries, sodium ion batteries, polymer batteries and graphene-based batteries • ARCI has been engaged in the development of indigenous technologies to produce electrode materials (cathode and anode) • ISRO is working on indigenization of Graphite based materials for Space applications. R&D efforts on advanced materials based on cylindrical cells aim to further improve energy density, cycle life and safety • Department of Atomic Energy has fabricated Sodium ion coin cell with an energy density of ~200Wh per kilogram using indigenously synthesized electrode material. A cost-effective lab scale synthesis procedure for electrode materials has been established and the technology has been transferred to several companies. Several efficient cathode materials for the next generation Li-S battery have also been developed. A polymer-based proton battery has also been designed and fabricated • CECRI has been engaged in cheaper iron based redox flow batteries for stationary energy storage applications. They have also focused on scaling up the synthesis of high-power Li-ion battery materials and utilizing electrospun nanofibers as functional materials for Lithium-Sulfur batteries. They are also developing new magnesium-sulfur (Mg-S) battery chemistry and electrodes through synthesis, characterization, and simulations.			

Strategies for critical battery mineral supply chain resilience – action plan until 2030

Strategic intervention	Action plan
Domestic exploration, mining and refining of critical mineral resources	• National stockpiling of refined mineral precursors used in LIB electrodes • Incentives for critical battery mineral exploration, mining and extraction through appropriate royalty and tax regimes • PLI for setting up critical mineral processing / refining units, especially for Li_2CO_3 / LiOH, $NiSO_4$, $CoSO_4$ and Spherical graphite • Production linked incentives for extraction of critical minerals through recycling LIBs
Overseas exploration and mining of critical mineral resources	• Strengthen Indian missions in critical mineral bearing foreign countries to facilitate due diligence of greenfield / brownfield mining assets, acquisition and investment by Indian companies • Strengthen KABIL to plan and undertake joint exploration, mining activities in critical mineral bearing foreign countries
Establish supply chain linkages with friendly foreign countries	• "G20 Critical Minerals Security Partnership" (G20-CMSP) should focus on building resilient supply chain of critical battery minerals, including stockpiles in different member countries as per comparative advantages in extraction and processing • Key stakeholders should prioritize Critical Battery Minerals Supply Chain as a key pillar of Indo-Pacific economic framework and a key factor in diplomatic outreach with mineral bearing foreign countries

R&D to develop recycling, extraction technologies and find earth abundant alternatives to critical battery minerals	• Formulate national R&D grand challenge for:
	  • developing high performance LIB electrodes made from earth abundant alternatives
	  • direct lithium extraction technologies from seawater that can selectively separate lithium from sea water using physical or chemical processes

Domestic exploration, mining and refining of critical battery minerals (Li, Ni, Co and Graphite)

Key stakeholders and action plan until 2030

1

National stockpiling of refined mineral precursors used in LIB electrodes

Strategic reserves of battery mineral precursors can act as buffer against global supply chain disruptions and extreme volatility in commodity prices

Key stakeholders: Ministry of Mines and KABIL

2

Incentives for critical battery mineral exploration and mining through appropriate royalty and tax regimes

Key stakeholders: Ministry of Mines, state governments of J&K, Odisha, Jharkhand, Nagaland, Tamil Nadu and others with identified mineral bearing resources

3

PLI scheme for setting up critical battery mineral processing / refining units from ore concentrates

Key stakeholders: Department of Chemicals & Petrochemicals for battery grade Li precursors from ore concentrates; Ministry of Mines for battery grade Ni, Co and Spherical Graphite commodities

4

PLI scheme for extraction of critical battery minerals from recycling used LIBs

Key stakeholders: NITI Aayog and Ministry of Environment & Forests for regulated mechanism involving collection and transportation of used Li-ion batteries from end users to OEMs / recycling companies

Overseas exploration and mining of critical battery mineral resources (Li, Ni and Co)

Key stakeholders and action plan until 2030

1

Strengthen Indian missions in critical mineral bearing foreign countries to facilitate due diligence of greenfield / brownfield mining assets, acquisition and investment by Indian companies
Technical assistance from domain experts in critical battery mineral resources exploration, extraction, asset due diligence and acquisitions in India's foreign missions of critical mineral bearing countries can add significant value

Key stakeholders:
- Indian missions in Australia, Chile, Bolivia, Argentina, DRC, Indonesia, etc.
- Ministry of External Affairs, Government of India
- NITI Aayog
- KABIL

2

Strengthen KABIL to accelerate plan and undertake exploration, mining activities in critical mineral bearing foreign countries

Institutional capacity building and resources for undertaking technology enabled reconnaissance and prospecting activities, due diligence for economic viability of mining operations, environmental and social impact assessment, compliance with local laws, etc.

Key stakeholders: Ministry of Mines, NITI Aayog, NALCO, HCL, MECL

Establish supply chain linkages with friendly foreign countries

Key stakeholders and action plan until 2030

1

“G20 Critical Minerals Security Partnership” (G20-CMSP)

CMSP should focus on building resilient supply chain of critical battery minerals, including stockpiles in different member countries, as per comparative advantages in extraction and processing. Joint technology development collaborations for chemical processing from ore concentrates, recycling etc. should also be focused.

Key stakeholders:
- Ministry of External Affairs
- Ministry of Mines
- G20 secretariat
- NITI Aayog

2

Critical Battery Minerals Supply Chain should be prioritized as a key pillar of Indo-Pacific economic framework and a key factor in diplomatic outreach with mineral bearing foreign countries

Key stakeholders:

- Ministry of External Affairs
- Ministry of Mines
- NITI Aayog

R&D to develop LIB recycling, extraction technologies, and earth abundant alternatives to critical battery minerals

Key stakeholders and action plan until 2030

1

Formulate national R&D grand challenge for developing high performance LIB electrodes made from earth abundant alternatives.

Focus should be cost optimization of active cathode and anode materials (< 20 USD/kWh) for mass adoption of LIBs.

Key stakeholders:
- NITI Aayog
- Ministry of Science & Technology
- DST
- ARCI
- ISRO
- DEA
- CERCI
- Academia

2

Formulate national R&D grand challenge for direct lithium extraction technologies from seawater that can selectively separate lithium from sea water using physical or chemical processes.

Focus should be extracting lithium with lower GHG emissions, energy consumption, higher yield, lower cost, less production time and many other advantages. Testing of discharge from Seawater desalination plants to evaluate lithium concentration and economics of DLE.

Key stakeholders:
- NITI Aayog
- Ministry of Science & Technology
- DST
- ARCI
- ISRO
- DEA
- CERCI

References and Annexure

08

Raw material requirements for producing 100 GWh/annum of LIBs

Critical materials	Demand to manufacture 100 GWh / annum LIBs (Thousand tons/annum)
Cathode active material	193
Graphite	98
Aluminum	91
Copper	41
Electrolyte: $LiPF_6$	8

Chemical precursors	Demand to manufacture ~193 thousand ton/annum active cathode material (Thousand tons/annum)
Li_2CO_3	56
$NiSO_4$	53
$CoSO_4$	48

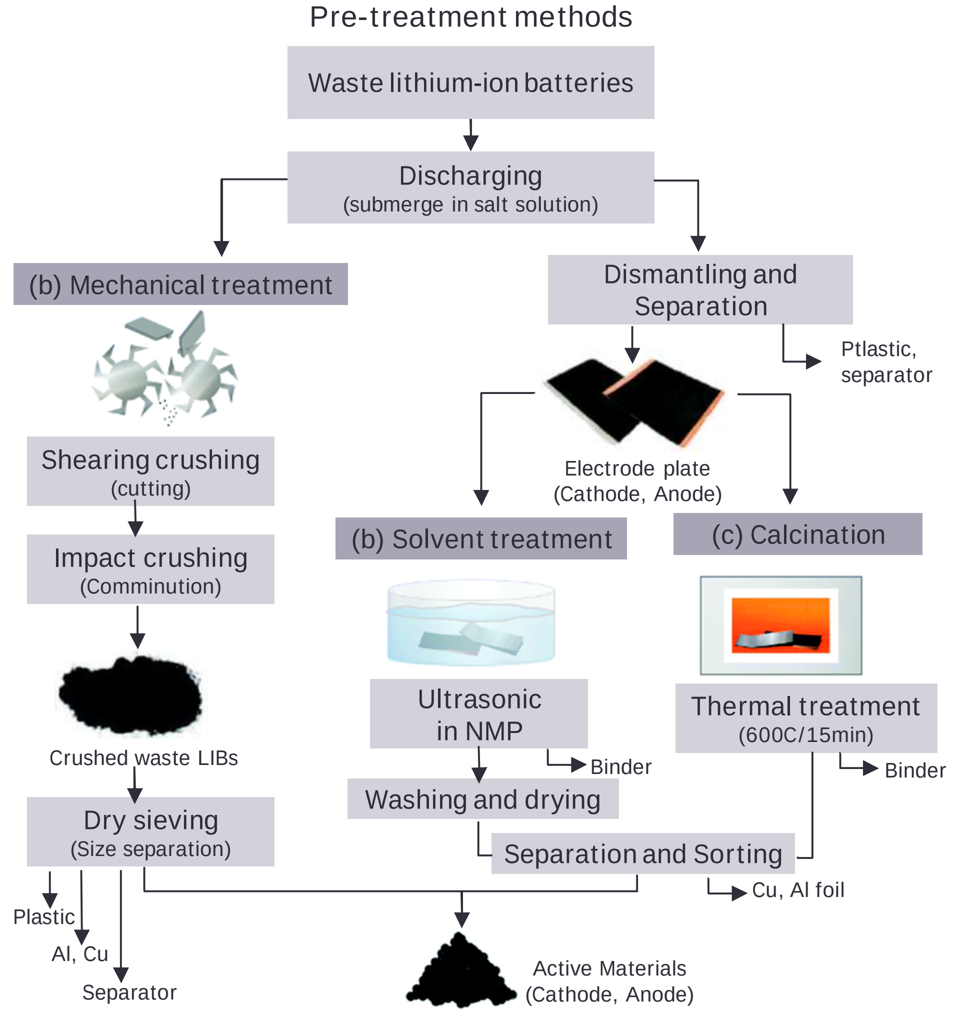
Demand to manufacture 100 GWh/annum LIBs (Thousand tons/annum)	
Li_2CO_3	56
$LiOH.H_2O$*	64

Input Materials	Inventory required for 1 ton Li_2CO_3	Inventory required for 1 ton $LiOH.H_2O$	Unit	Demand to manufacture 56 thousand tons/annum Li_2CO_3	Demand to manufacture 64 thousand tons/annum $Li_2OH.H_2O$	Demand to manufacture 100GWh/annum LIBs (12% Li_2CO_3 and 88% $LiOH.H_2O$)**	Unit
Spodumene concentrate	7.3	6.4	ton	409	408	408	thousand ton
H_2SO_4	1.71	1.52	ton	96	97	96	thousand ton
Na_2CO_3	2.05	0.03	ton	115	2	15	thousand ton
NaOH	0.05	0.67	ton	3	43	38	thousand ton
$CaCO_3$	0.70	0.60	ton	39	38	38	thousand ton
Fresh water	40.00	11.24	m^3	2200	715	892	thousand ton

*Li_2CO3 to $LiOH.H_2O$ conversion factor of 1.14 is applied by conserving the mass of Lithium.

** By 2030, global demand for LiOH is estimated as ~1.4 million metric tons LCE (~1.59 million metric tons $LiOH.H_2O$), while Li_2CO_3 demand as 218,000 metric tons LCE as per the BNEF article. This gives the demand ratio of Li_2CO_3 to $LiOH.H_2O$ as 12:88. (Will the Real Lithium Demand Please Stand Up? Challenging the 1Mt-by-2025 Orthodoxy | BloombergNEF (bnef.com))

Process flow of li-ion battery recycling



Pre-treatment methods

Waste lithium-ion batteries

Discharging
(submerge in salt solution)

(b) Mechanical treatment

Shearing crushing
(cutting)

Impact crushing
(Comminution)

Crushed waste LIBs

Dry sieving
(Size separation)

Plastic

Al, Cu

Separator

Dismantling and Separation

Ptlastic, separator

Electrode plate
(Cathode, Anode)

(b) Solvent treatment

Ultrasonic in NMP

Binder

Washing and drying

(c) Calcination

Thermal treatment
(600C/15min)

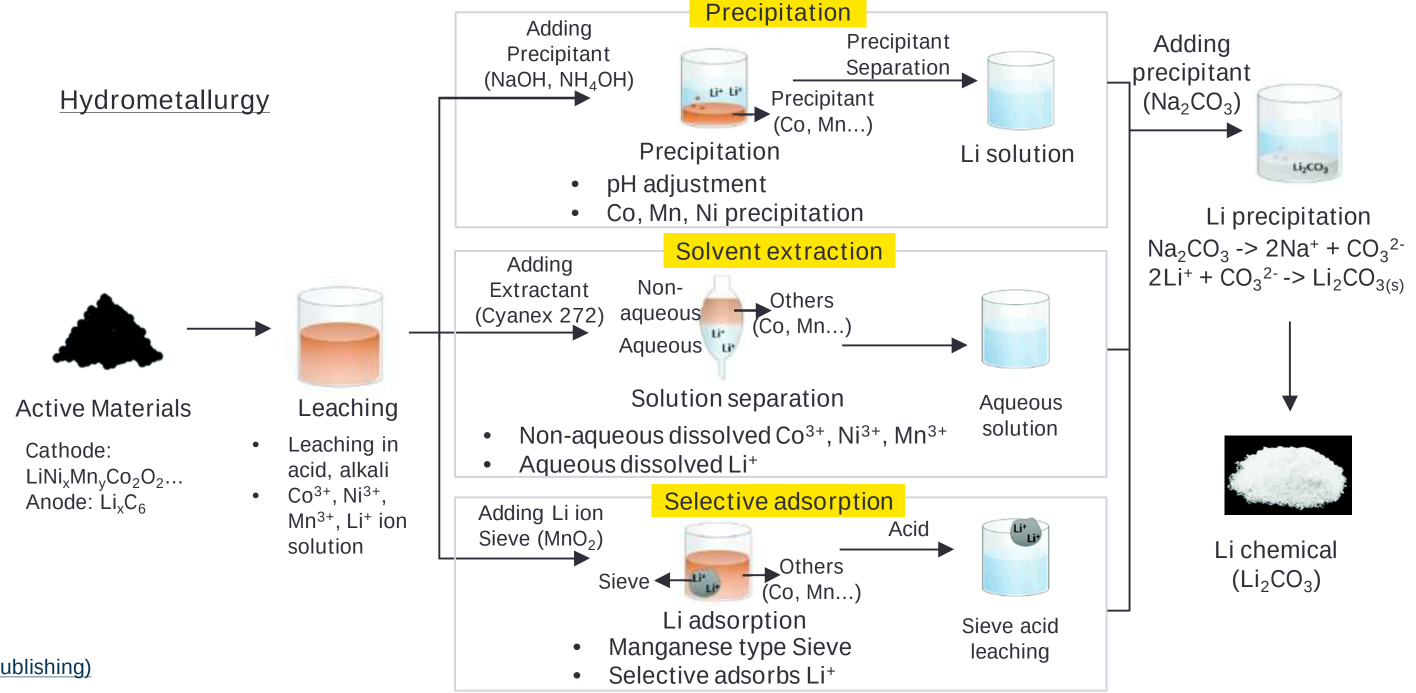
Binder

Separation and Sorting

Cu, Al foil

Active Materials
(Cathode, Anode)

Recycling Method	Pros	Cons	Recovered Materials
Hydrometallurgy (most common)	Applicable to any battery chemistry and configuration	Only economical for batteries containing Co and Ni	Copper, Aluminum, cobalt, Li_2CO_3. Anode is destroyed
Pyrometallurgy (smelting)	Applicable to any battery chemistry and configuration	Only economical for batteries containing Co and Ni; Gas clean-up required to avoid release of toxic substances	Cobalt, nickel, copper, some iron. Anode is destroyed
Direct Recycling (supercritical CO2)	Almost all battery materials can be recovered	Recovered material may not perform as well as virgin material, mixing cathode materials could reduce value of recycled product	Almost all components (except separators)



Hydrometallurgy

Active Materials

Cathode:
$LiNi_xMn_yCo_2O_2$...
Anode: Li_xC_6

Leaching

- Leaching in acid, alkali
- Co^{3+}, Ni^{3+}, Mn^{3+}, Li^+ ion solution

Precipitation

Adding Precipitant ($NaOH$, NH_4OH)

Precipitant Separation

Precipitant (Co, Mn...)

Li solution

Precipitation

- pH adjustment
- Co, Mn, Ni precipitation

Solvent extraction

Adding Extractant (Cyanex 272)

Non-aqueous

Aqueous

Others (Co, Mn...)

Aqueous solution

Solution separation

- Non-aqueous dissolved Co^{3+}, Ni^{3+}, Mn^{3+}
- Aqueous dissolved Li^+

Selective adsorption

Adding Li ion Sieve (MnO_2)

Acid

Sieve

Others (Co, Mn...)

Sieve acid leaching

Li adsorption

- Manganese type Sieve
- Selective adsorbs Li^+

Adding precipitant (Na_2CO_3)

Li precipitation

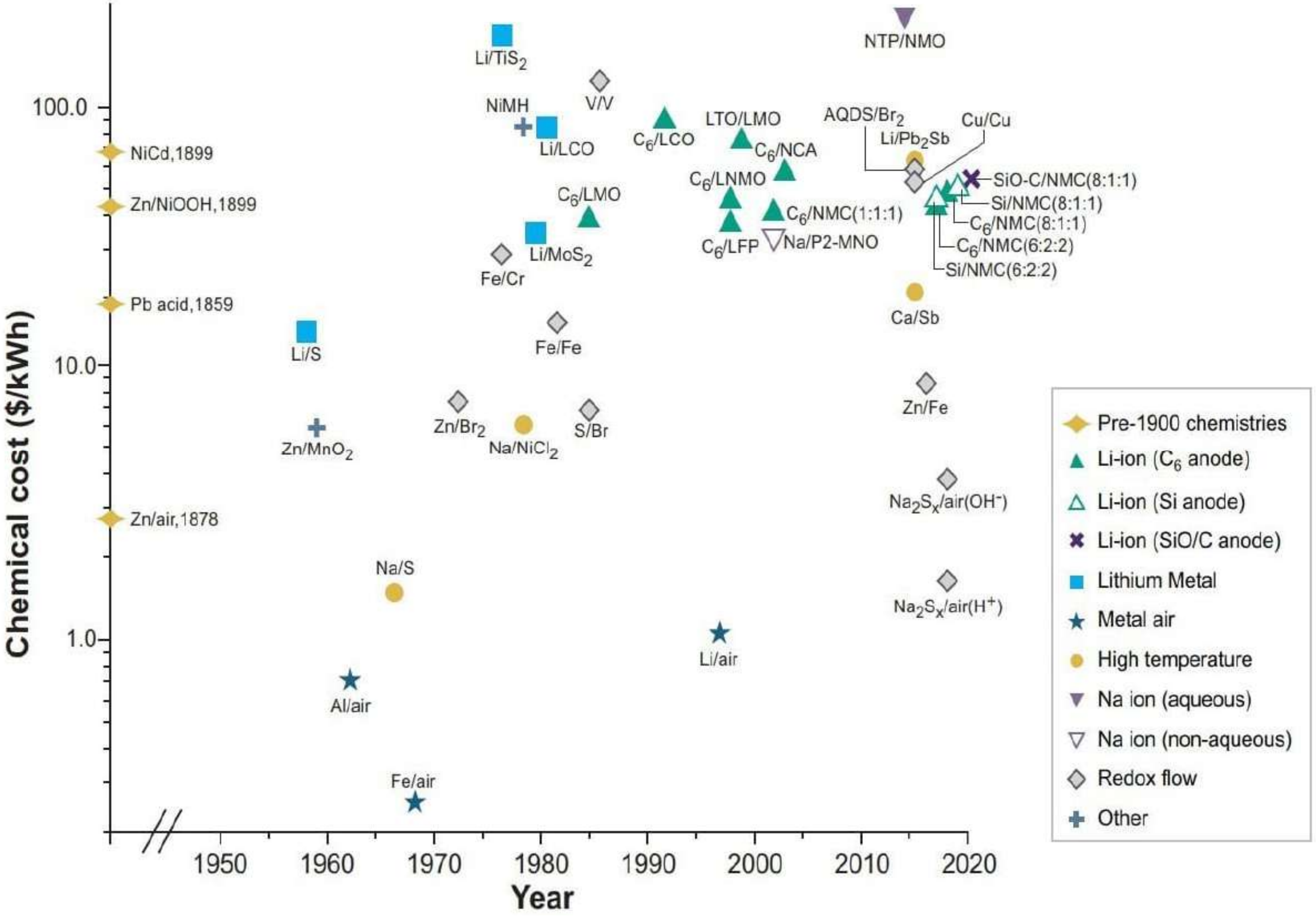
$Na_2CO_3 \rightarrow 2Na^+ + CO_3^{2-}$

$2Li^+ + CO_3^{2-} \rightarrow Li_2CO_{3(s)}$

Li chemical (Li_2CO_3)

Source: Economics and Challenges of Li-Ion Battery Recycling from End-of-Life Vehicles (nrel.gov), Technologies of lithium recycling from waste lithium ion batteries: a review - Materials Advances (RSC Publishing)

Chemical cost of stored energy for existing and emerging battery electro chemistries



Source: MIT Study on the Future of Energy Storage, June 2022

- The chemical cost of stored energy for battery electro chemistries is shown against the year in which the system first appeared in the public domain. Technologies pre-1900 are shown against the left axis.
- Chemical cost is calculated as the cost of the negative electrode material, positive electrode material, and electrolyte, divided by the stored energy.
- Abbreviations: LMO = lithium manganese oxide, LCO = lithium cobalt oxide, LFP = lithium iron phosphate, LNMO = lithium nickel manganese oxide, LTO = lithium titanium oxide, NMC = lithium nickel manganese cobalt oxide, NCA = lithium nickel cobalt aluminum oxide, P2-MN = P2-type sodium manganese nickel oxide, NTP = sodium titanium phosphate, NMO = nickel manganese oxide, NiCd = nickel–cadmium, NiMH = nickel metal hydride, AQDS = 9,10-anthraquinone-2,7-disulfonic acid

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