VALUE ADDING OPPORTUNITIES FOR AUSTRALIAN BATTERY CRITICAL MINERALS

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FUTURE BATTERY INDUSTRIES CRC

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Context: Critical Minerals/Metals as Group

- Critical Minerals (CMs): An mineral economic term, not a technical one.
- Geopolitical drivers are typical in risks to supply chains disruptions which makes minerals critical if those minerals are essential for modern technologies, and in particular for the modern energy transition.
- Prices are volatile and supplies are at risk due to many possible disruptions by single (or a few) big players along value chain
- Some part of the value chain normally passes through a country that often threatens free market operation and known geopolitical risks
- Processing and chemistries very diverse. No commonality exists that would allow generalisation across the wide range of CMs. Even when they are used in the same application, e.g. batteries, there is no similarity amongst battery CMs of lithium, nickel, manganese, high purity alumina and graphite (and/or phosphate in the case of LFP batteries).
  - Their geological occurrence, mineralogy, mining, waste products, chemistry, processing and refining differ widely.
- Some CMs, such as Li-bearing spodumene is viewed as an industrial mineral of the lithophile group of elements. Others, such as nickel, belongs to the chalcophile group of elements and scarcer base metals. The Platinum Group Metals (PGMs), essential in the green hydrogen equipment supply chain, are extremely scarce and also classified as precious metals. Unlike gold, PGMs are critical and gold not.
- Many CMs are by-products from the primary production of other minerals.

Natural Flake Graphite

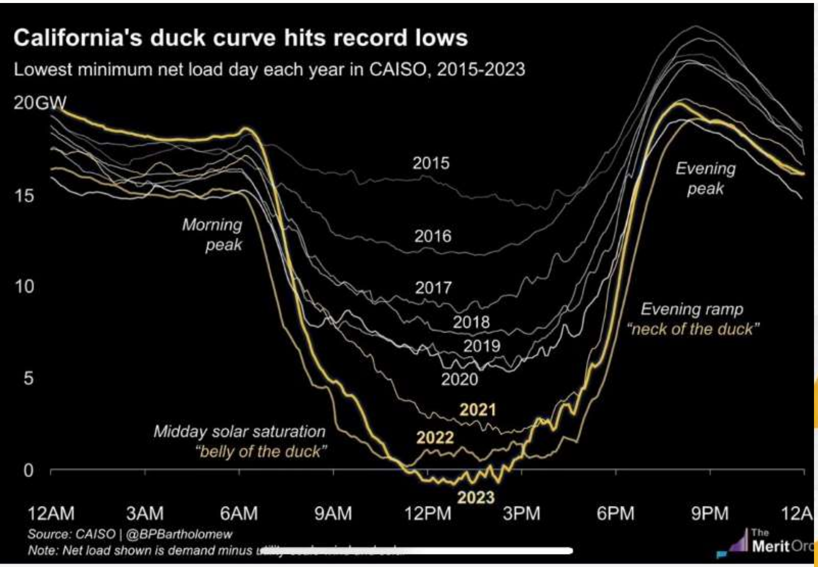
Spodumene (Li)

HPA (Alumina)

Pentlandite (Ni)

Platinum

The pictures shaping the world of battery minerals/metals

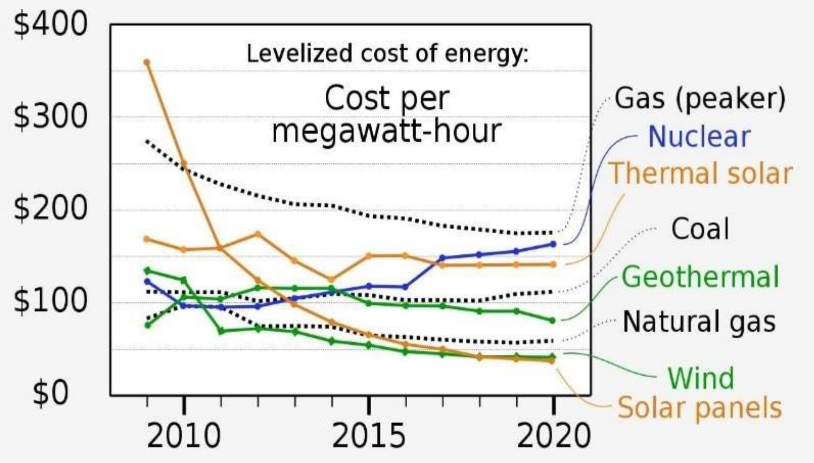


California's duck curve hits record lows

Lowest minimum net load day each year in CAISO, 2015-2023

Source: CAISO | @BPBartholomew

Note: Net load shown is demand minus u



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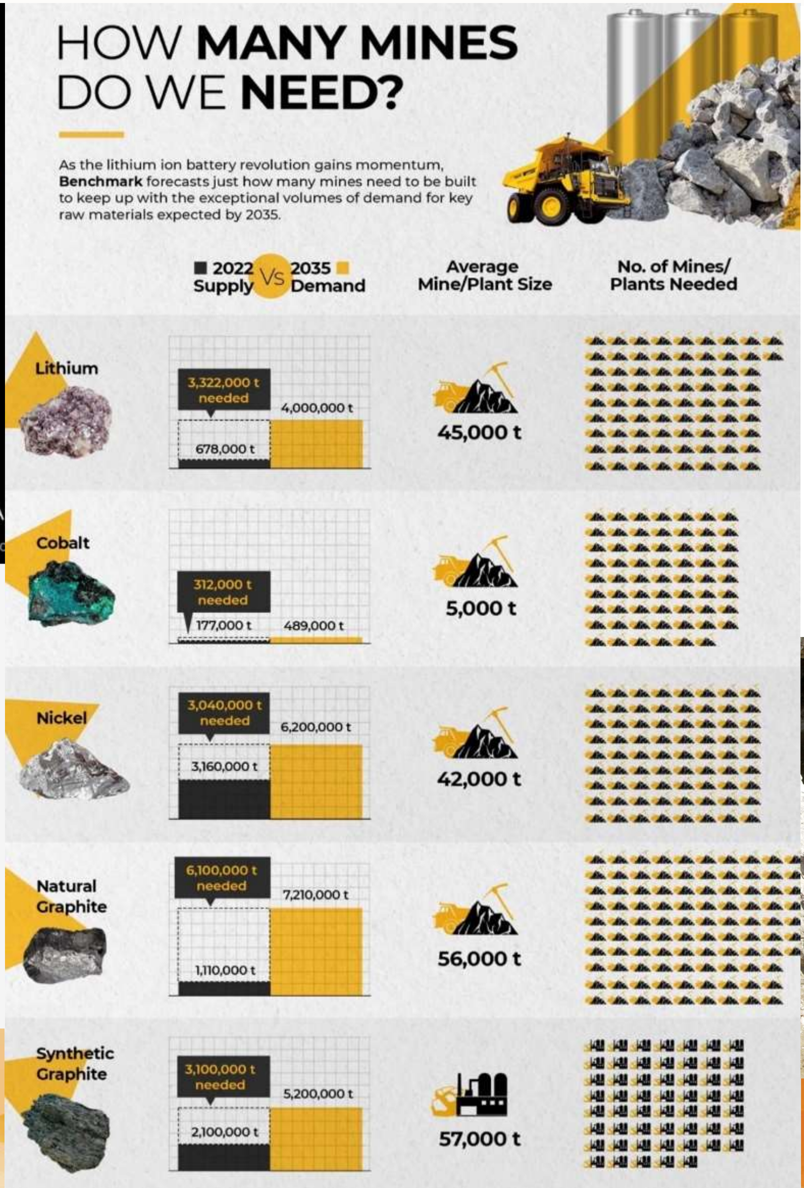
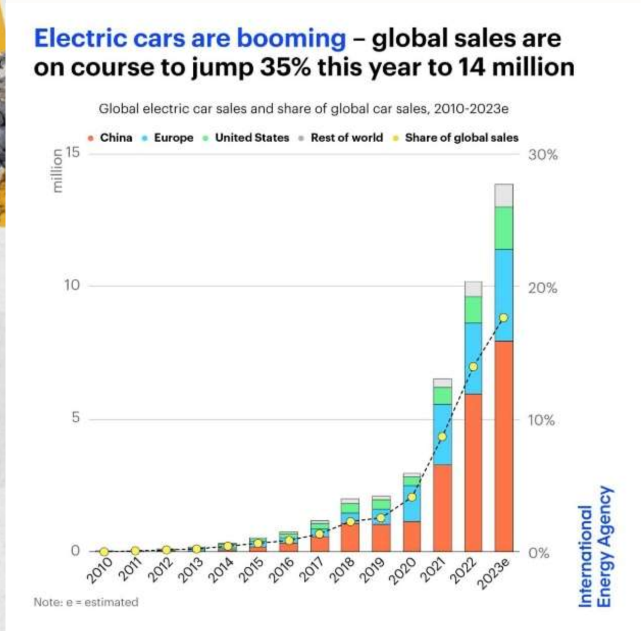


HOW **MANY MINES** DO WE **NEED?**

As the lithium ion battery revolution gains momentum, **Benchmark** forecasts just how many mines need to be built to keep up with the exceptional volumes of demand for key raw materials expected by 2035.

	2022 Supply	2035 Demand		Average Mine/Plant Size
Lithium	678,000 t	4,000,000 t	3,322,000 t needed	45,000 t
Cobalt	177,000 t	489,000 t	312,000 t needed	5,000 t
Nickel	3,160,000 t	6,200,000 t	3,040,000 t needed	42,000 t
Natural Graphite	1,110,000 t	7,210,000 t	6,100,000 t needed	56,000 t
Synthetic Graphite	2,100,000 t	5,200,000 t	3,100,000 t needed	57,000 t



Electric cars are booming – global sales are on course to jump 35% this year to 14 million

Global electric car sales and share of global car sales, 2010-2023e

Note: e = estimated

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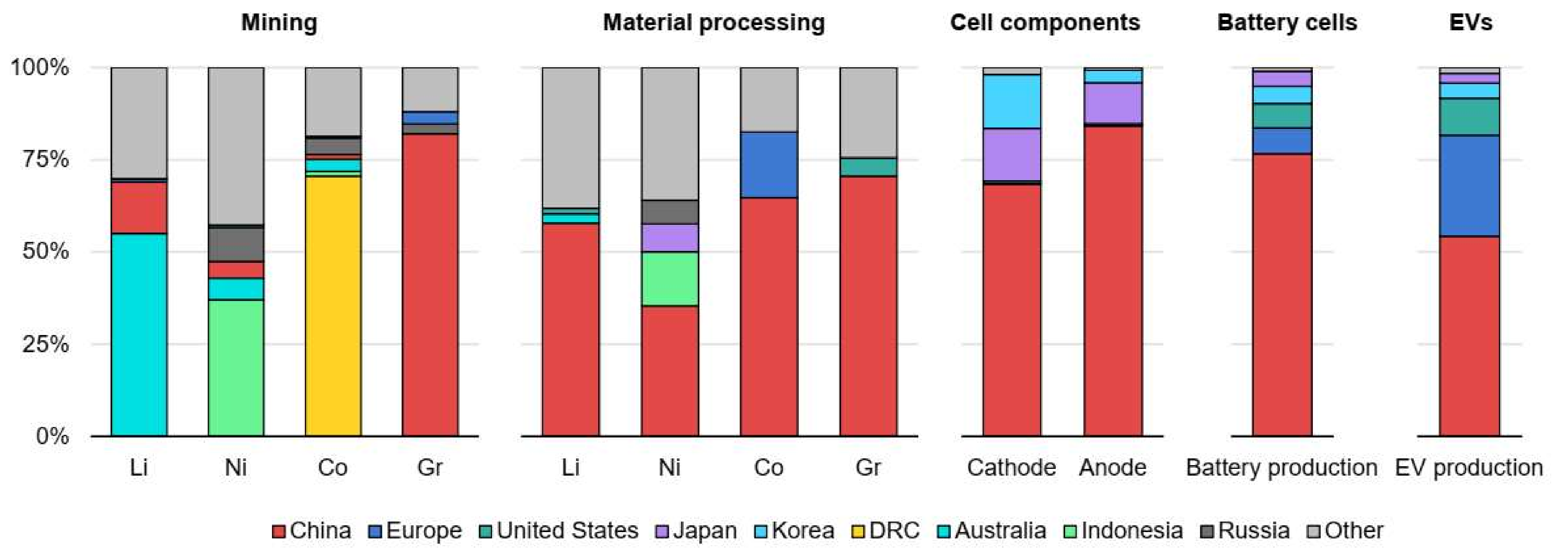
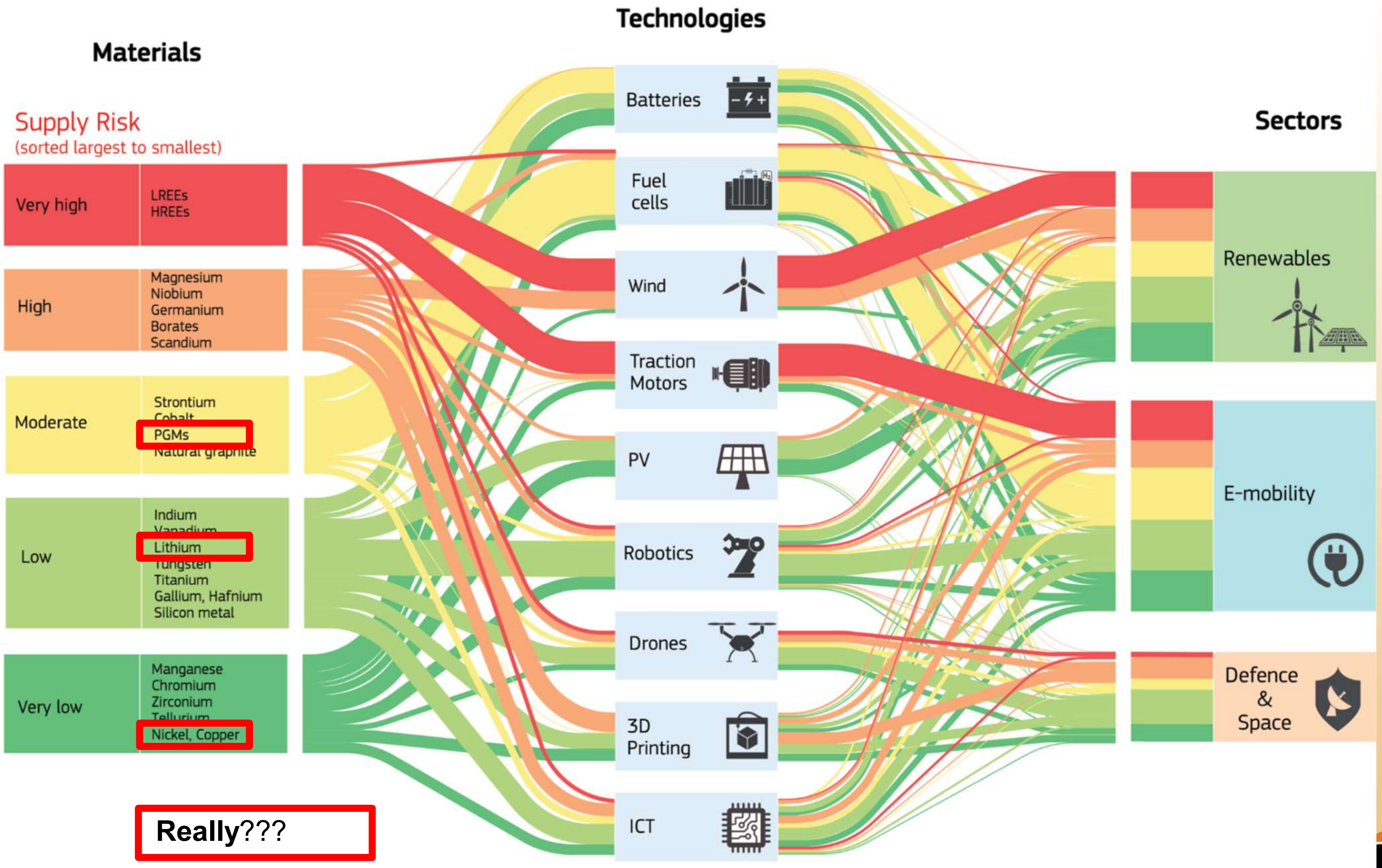
China still dominates the batter material supply chains



Graph sourced from IEA Report (www.iea.org): "Global Supply Chains of EV Batteries", 2022

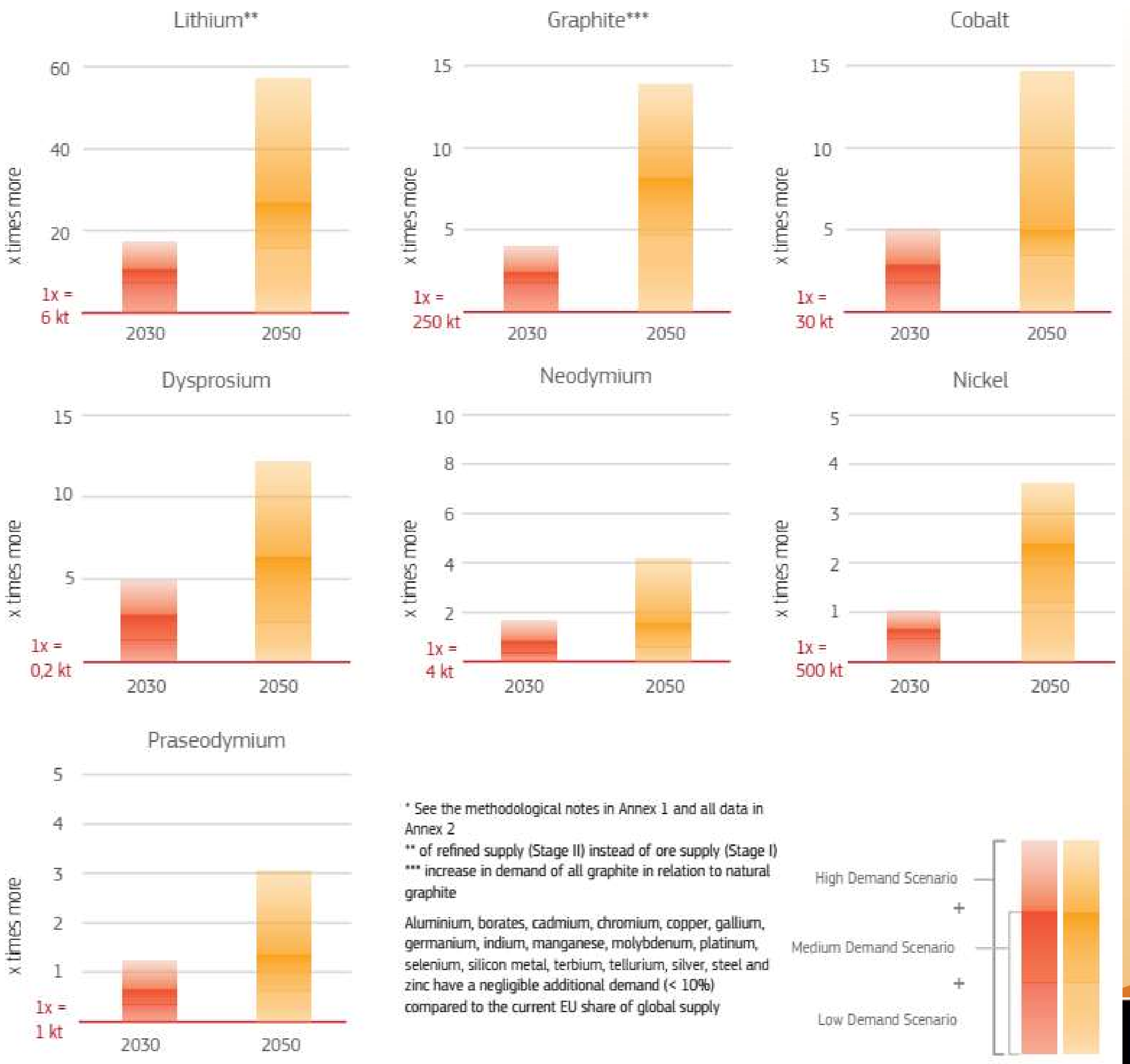
CMs in the Energy Transition, Defense, and Advanced Technology Markets (EU Example)

It is ***important to remove the criticality*** of CMs. Criticality is alleviated through redundancy in the supply chain and parallel pathways to remove bottlenecks.



Really???

Demand Growth in some Critical Minerals / Metals / Materials



* See the methodological notes in Annex 1 and all data in Annex 2

** of refined supply (Stage II) instead of ore supply (Stage I)

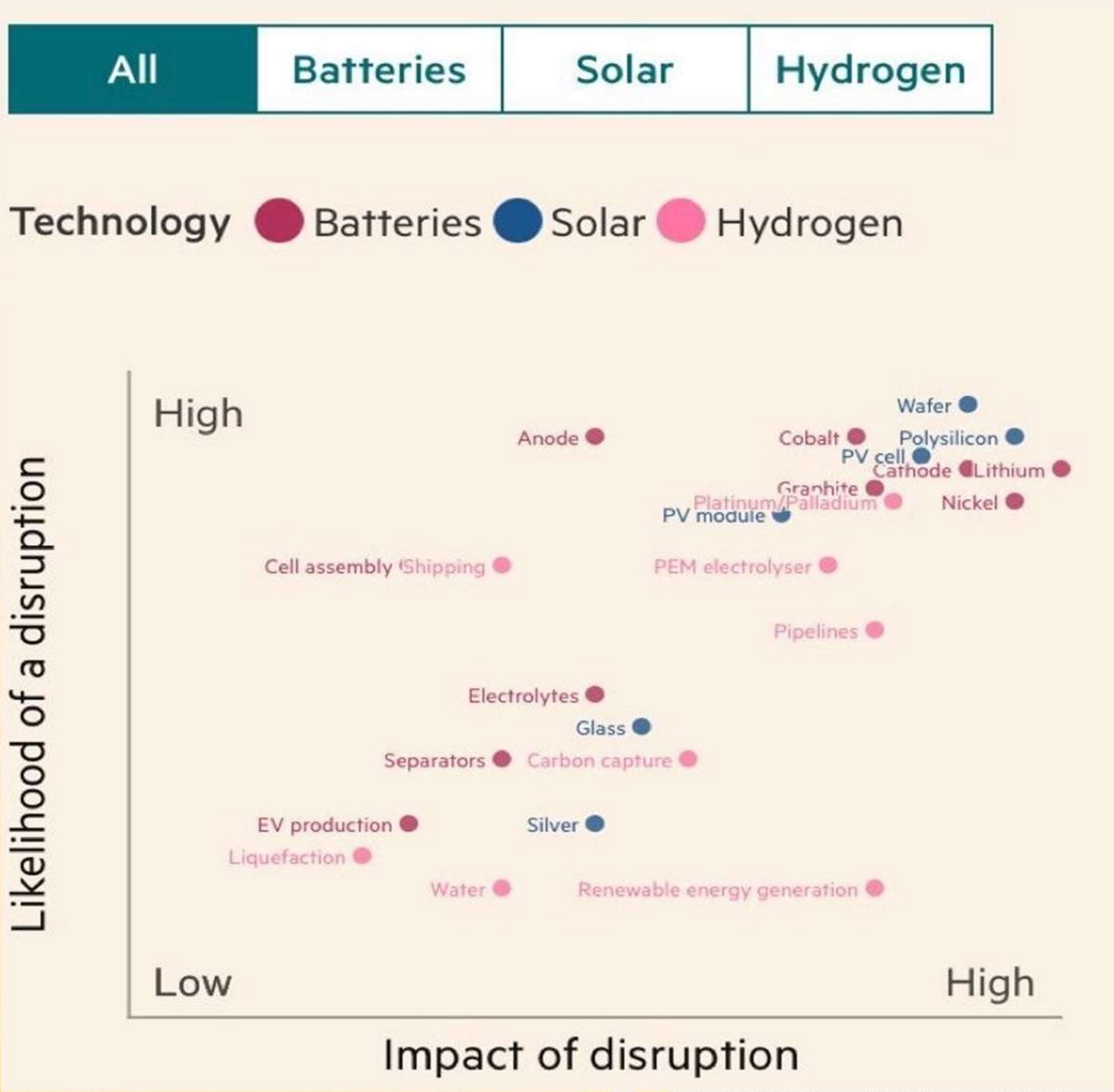
*** increase in demand of all graphite in relation to natural graphite

Aluminium, borates, cadmium, chromium, copper, gallium, germanium, indium, manganese, molybdenum, platinum, selenium, silicon metal, terbium, tellurium, silver, steel and zinc have a negligible additional demand (< 10%) compared to the current EU share of global supply

Innovation and the vulnerability to disruption:

Comparing the supply chain vulnerabilities of clean energy technologies

While innovation is often seen as positive, high rates of change and disruption may lead to “Osborne Effect”

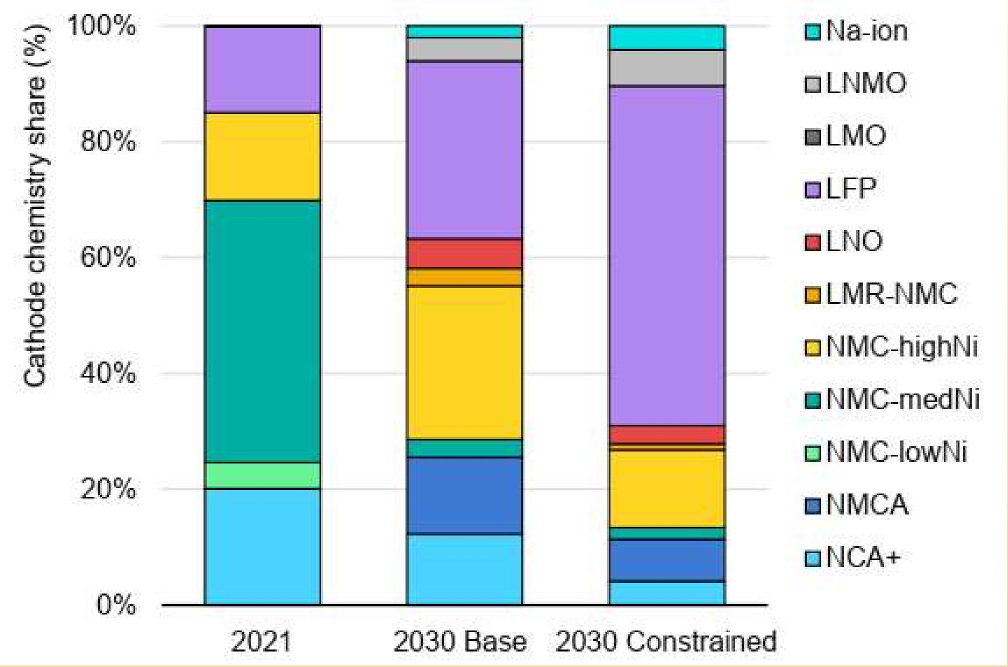


Source: International En

Anticipated changes in battery chemistries (excluding flow batteries):

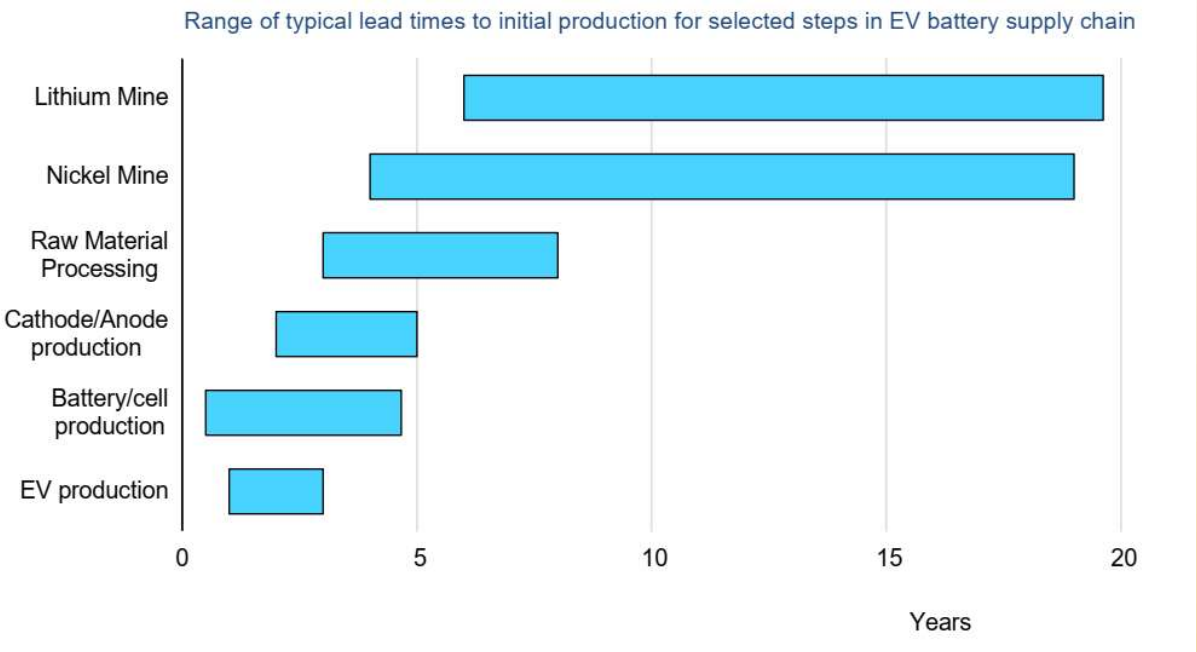
Battery cathode chemistries include:
Na-ion = sodium-ion.
LNMO =lithium nickel manganese oxide.
LMO = lithium manganese oxide.
LFP = lithium iron phosphate.
LNO = lithium nickel oxide.
LMR-NMC = lithium-manganese-rich NMC.
NMC = lithium nickel manganese cobalt oxide.
NMC-highNi includes: NMC811 and NMC9.5.5.
NMC-medNi includes: NMC532, NMC622 and NMC721.
NMC-lowNi includes: NMC333.
NMCA = lithium nickel manganese cobalt aluminium oxide.
NCA = lithium nickel cobalt aluminium oxide.
NCA+ includes: NCA85, NCA90, NCA92 and NCA95

*Sourced from IEA



Graph sourced from IEA Report (www.iea.org):
“Global Supply Chains of EV Batteries”, 2022

The disconnect in timelines to establish bring new capacity online



Graph sourced from IEA Report (www.iea.org): "Global Supply Chains of EV Batteries", 2022

There is a significant disconnect between the time to bring new EV manufacturing or battery production into production versus bringing new mines and refining capacity into production

Critical Minerals, Metals & Materials (C3M's) in the Clean Energy Transition: Environment, Social & Governance (ESG) as a common driver & context

- These C3Ms are key enablers of clean energy transition:
  - batteries, hydrogen, ammonia, solar PV, wind turbines, electric motors and generators/dynamo'.
- Clean energy target requires supply chain of C3Ms to be clean, be ESG compliant, and align with global SDG's.
- This implies decarbonisation of scope 1, 2, and 3 emissions of CO_2. In addition, the sourcing should be ethical, have ethical and responsible labour practices, and minimise impacts on potable water use, communities, and waste generation.
  - Mine electrification is happening apace to lower Scope 1 & 2 the missions, but refining and conversion to high concentration materials required to lower Scope 3 emissions, e.g. associated with shipping/transport.
  - Carbonation of mineral wastes with point source emissions of CO_2 can lead to both sequestration and valorisation.
  - Waste must be valorised where it is generated as far a possible and not end up in landfill.
- Circularity does not only imply end-of-life only but reuse and repurpose throughout the value chain.
- Electrification from a renewable grid would be instrumental to decarbonise mining, processing and refining as well as advanced materials production.
- These ESG drivers and decarbonisation determine the context for our mine and process design.
- In this light we will look at two examples:
  - Decarbonisation and electrification of spodumene conversion to LiOH.
  - Process intensification and decarbonisation of nickel and cobalt from disseminated sulphide resources

Sustainability in battery supply chains

Supply Side Constraints:

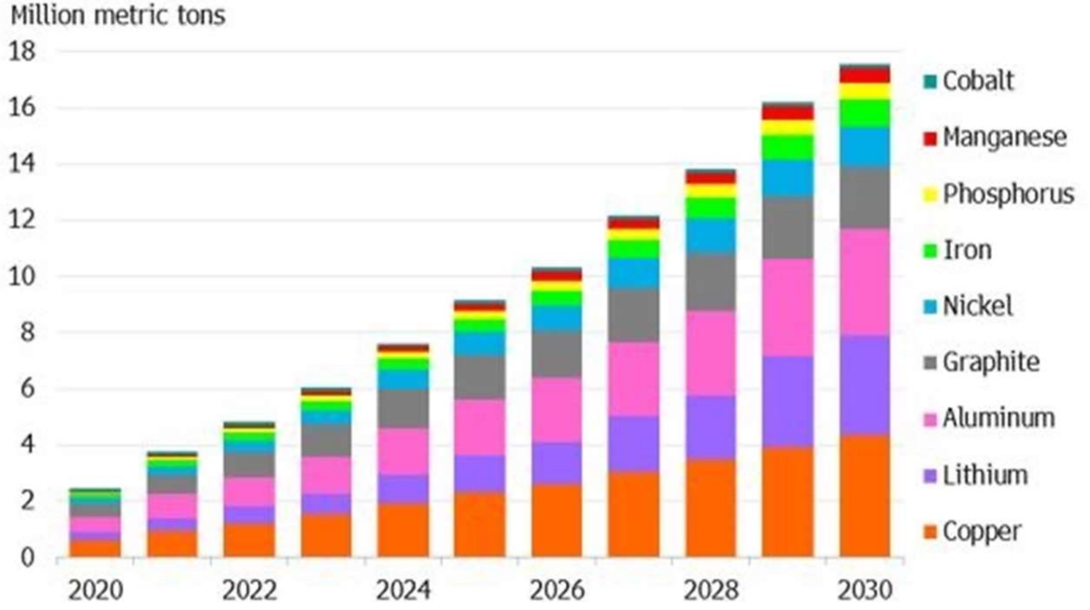
- Limited accessible Ni-Co-Mn-Li geologies
- Geopolitical stability
- Community & regional conflicts :Water use
- Community & regional conflicts: Waste
- Extent to which mining & processing can be made net-zero in terms of CO2 emissions
- Poor metallurgical processing recoveries and yields
- Ensuring “green” processes are in place to produce refined lithium, nickel and graphite
- Single, or limited, dominant players in the supply chain

The battery metal demand tsunami

- Li’s use is ubiquitous in cathode active materials, electrolyte and (sometimes) as anode material.
- Al is used as a foil in the cathode current collector but is also present in the cathode active materials, separator, and cathode and anode coatings (as high purity alumina).
- Fe appears in LFP and LFMP battery chemistries
- Cu foil is used as anode current collector, but it also underpin the global “electrify everything” drive
- Not shown here are the metals such as vanadium in redox flow batteries for stationary energy storage systems
- Phosphorus is used in Li-ion electrolytes ($LiPF_6$) and in LFP and LFMP battery cathode materials
- In addition to the battery metals, the Rare Earths are important, particularly for the magnets in electrical motors (EV’s) and wind turbines for electrical power generation

Accelerating Demand

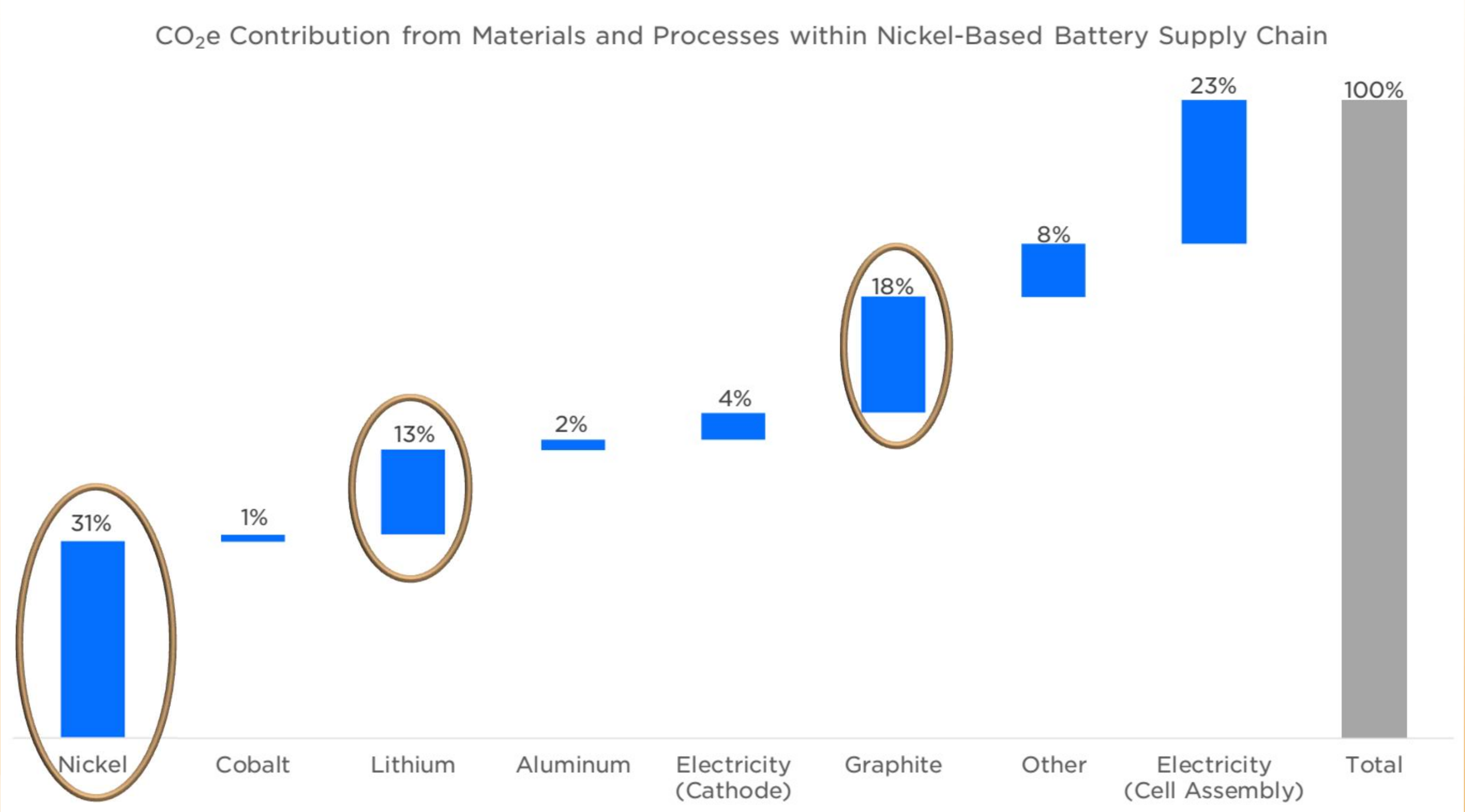
Metals demand from lithium-ion batteries is expected to top 17 million tons in 2030



Source: BloombergNEF. Note: Metals demand occurs at the mine mouth, one year before battery demand.

The production of the renewable technologies and energy storage technologies should be sustainable and should have a minimal carbon footprint

Contributions to Carbon Intensity of NMC LiB's

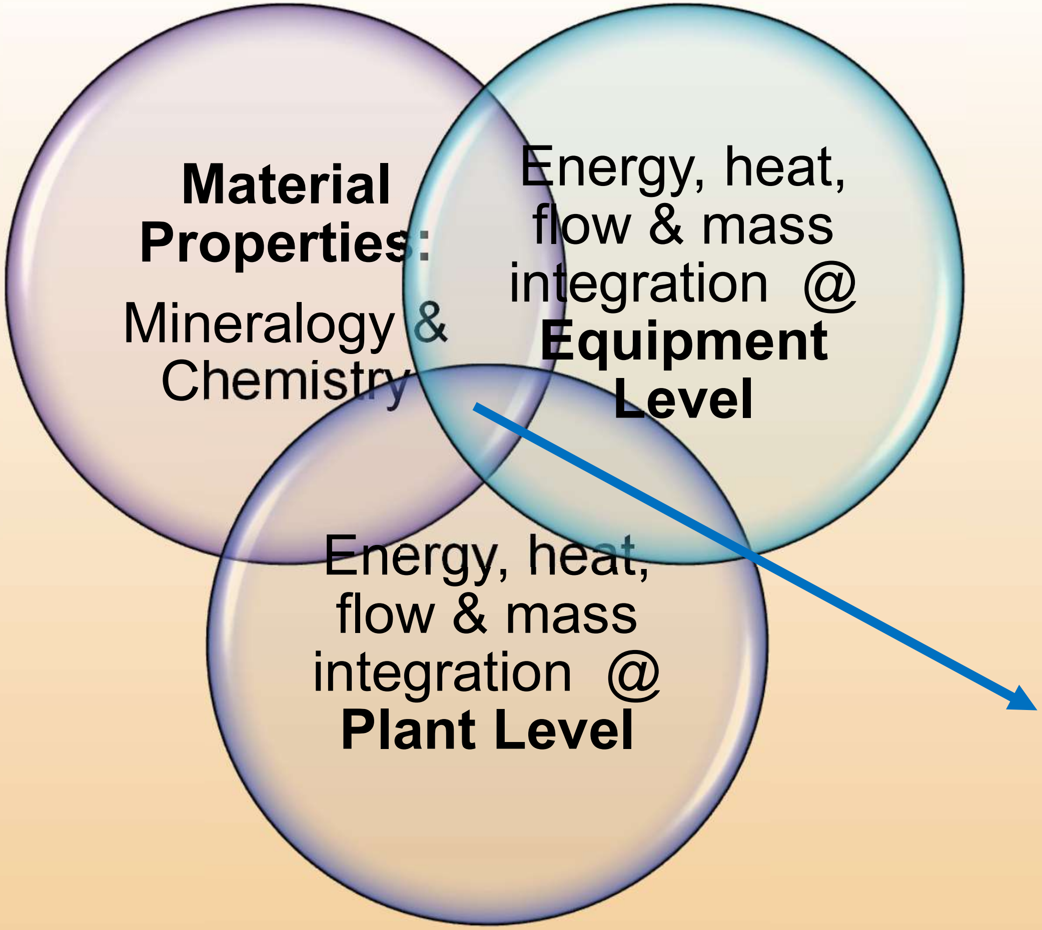


Source: Tesla Impact Report 2021

Major Carbon Contributors: Nickel, Lithium and Graphite

- Nickel, lithium and graphite all derive from ores that needs to be:
    - Mined
    - Crushed
    - Ground/milled
    - Concentrated through gravity & flotation technology
- The recoveries that can be achieved upstream in the concentrator is often constrained by the grade requirements of the downstream process (calcination, smelting, pressure leaching, spheroinisation in the case of graphite)
- Scope 1,2 & 3 emissions need to be evaluated, including the production of reagents, transport & energy mix
- Poor concentrator recovery implies that a significant amount of the energy used in crushing & grinding is wasted in unrecovered material to the tailings dam
    - *Just increasing the metallurgical recovery already significantly lowers the carbon footprint per metal unit produced*
- Finding metallurgical methods that can eliminate smelting (and its grade constraints), perform calcination in ways that minimize interparticle contact and clinkering, and improves spheroinisaton and graphitization yields (or replace synthetic graphite with high-yield, spheroinised natural graphite) can significantly lower the carbon footprint
- While improvements in heat transfer and fluid flow in the various thermal devices may lead to improvements, the extent of these improvements are highly dependent on the metallurgical and mineralogical nature of the materials (metal of interest and gangue minerals)

Multifaceted approach to decarbonization in lithium processing



Material Properties:

Mineralogy & Chemistry

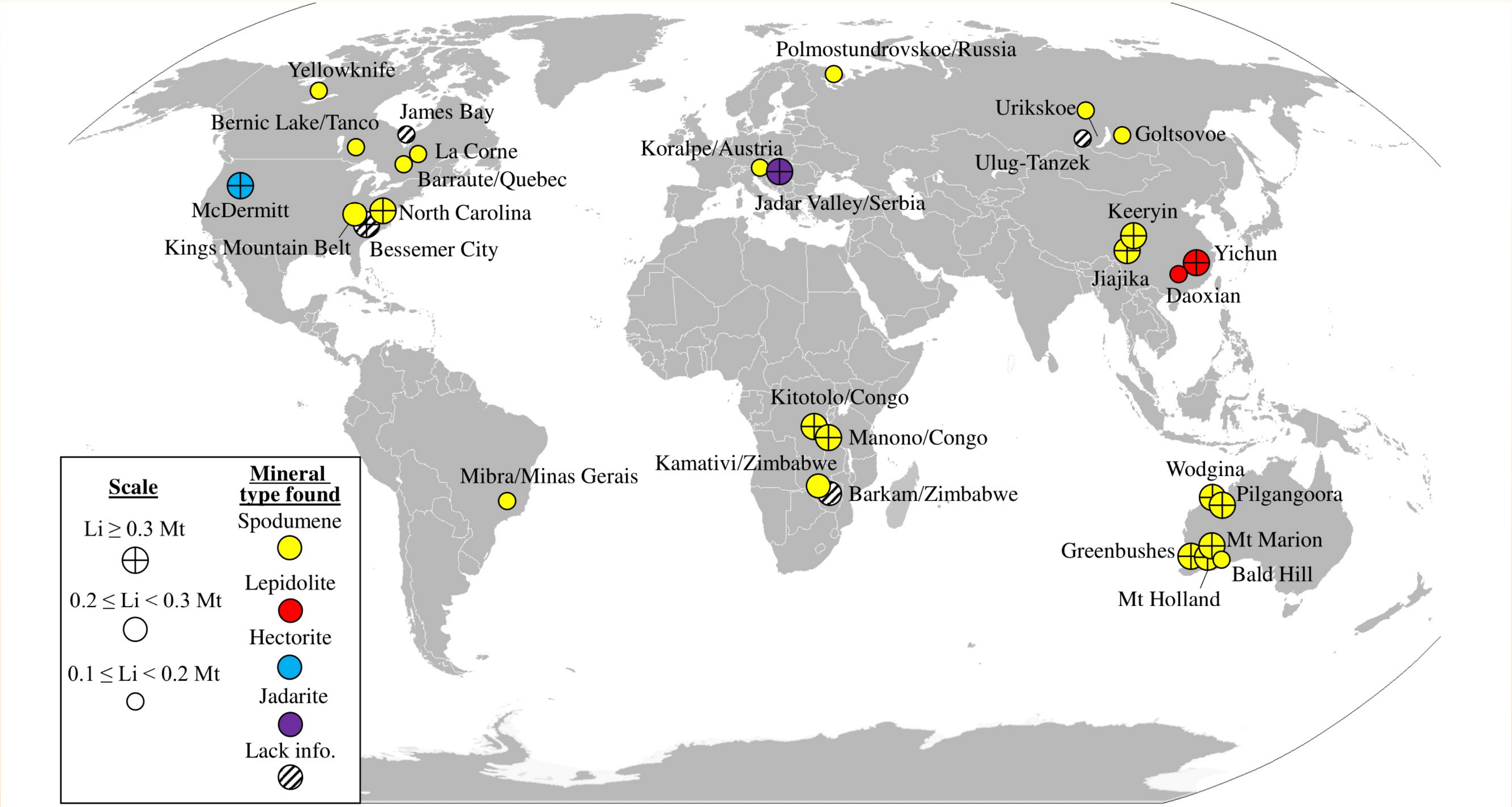
Energy, heat, flow & mass integration @ **Equipment Level**

Energy, heat, flow & mass integration @ **Plant Level**

Maximum Opportunity for Decarbonisation

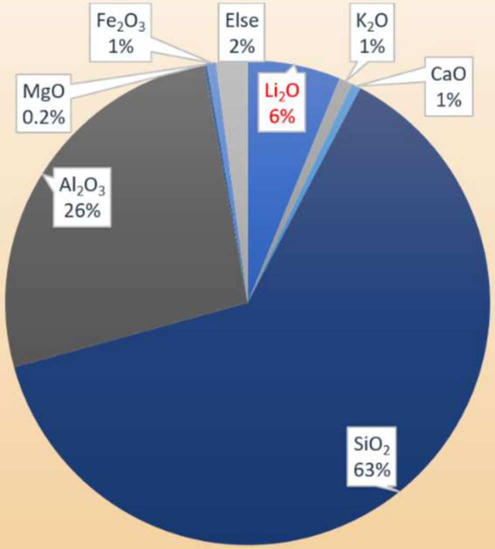
Lithium from spodumene: Challenges & Opportunities

Major lithium mineral deposits (≥0.1 Mt Li)



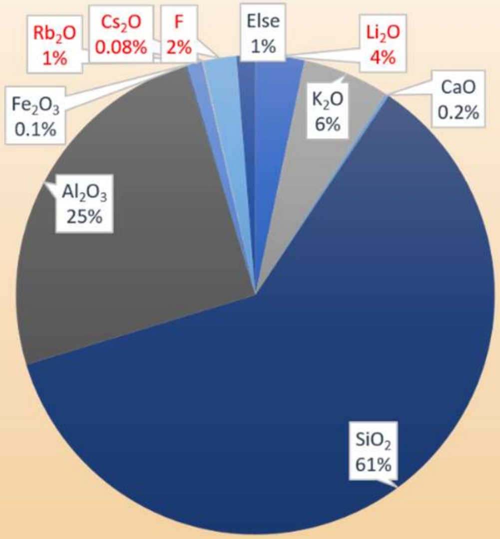
Typical lithium-bearing concentrate

Spodumene concentrate
(Greenbushes, WA)



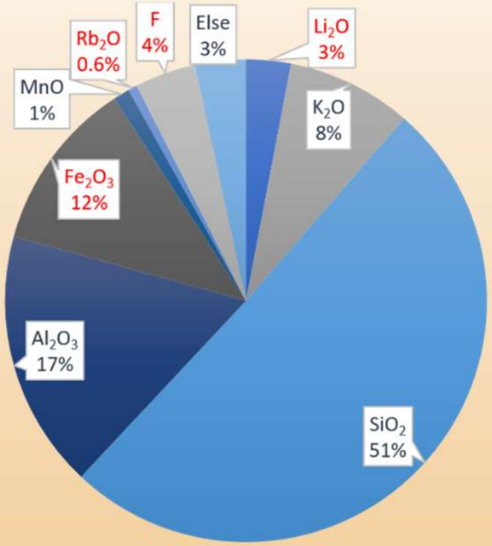
- Higher lithium grade
- Simpler compositions
- Less impurities

Lepidolite concentrate
(Yichun, China)



- Lower lithium grade
- Value-added rubidium, cesium
- Harmful fluorine

Zinnwaldite concentrate
(Zinnwald, Germany)



- More lower lithium grade
- Value-added rubidium
- Harmful fluorine
- High iron content

Conventional H_2SO_4 roasting method

- Proven effective to β-spodumene (con. H_2SO_4) and lepidolite (~85% H_2SO_4)
- Voluminous residue to be treated
  - Al-Si based residue, silica;
  - Calcium sulfate, calcium carbonate, Mg/Mn/Al/Fe hydroxides
- Noticeable lithium loss during impurity removal, *esp*. for lepidolite
- Flooded sodium sulphate by-product
- Lepidolite
  - Release of HF, SiF_4 gases
  - Further treatment of mixed alums (K, Rb, Cs)

Fluorine-based leaching methods

- Proven effective to α-spodumene, β-spodumene and lepidolite
- Options:

Hydrofluoric acid (HF)

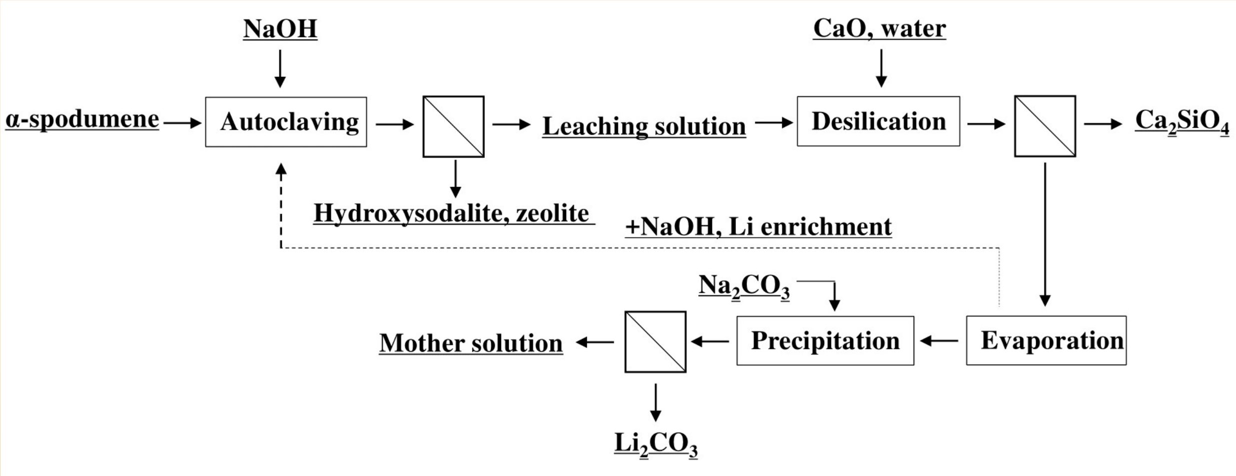
HF/ fluorosilicic acid (H_2SiF_6) + H_2SO_4

Fluorite (CaF_2) + H_2SO_4

- Energy saving (75-230 ^{o}C), and high extractions;
- Fluorine removal better as early as possible, *e.g.* before alum crystallization;
- More sensible for silicate minerals with fluorine originally contained;
- Future research on mechanism, equipment design, safety control, *etc*;

Alkali roasting/autoclaving methods

- Proven effective to α-spodumene, β-spodumene and lepidolite;
- Alkali options:
  - Caustic (NaOH)
  - Lime/limewater ($CaO/Ca(OH)_2$)
- Caustic autoclaving for α-spodumene
  - Phase transfer (~1050 °C) avoided
  - High caustic consumption, *e.g.* 0.6 tonne caustic/tonne feed (5.5% Li_2O)
- Alkaline (caustic, lime/limewater/limestone) treatment is also capable of directly producing LiOH product.



NaOH

CaO, water

α-spodumene → Autoclaving → Leaching solution → Desilication → Ca_2SiO_4

Hydroxysodalite, zeolite

+NaOH, Li enrichment

Na_2CO_3

Mother solution ← Precipitation ← Evaporation

Li_2CO_3

Salt roasting/autoclaving methods

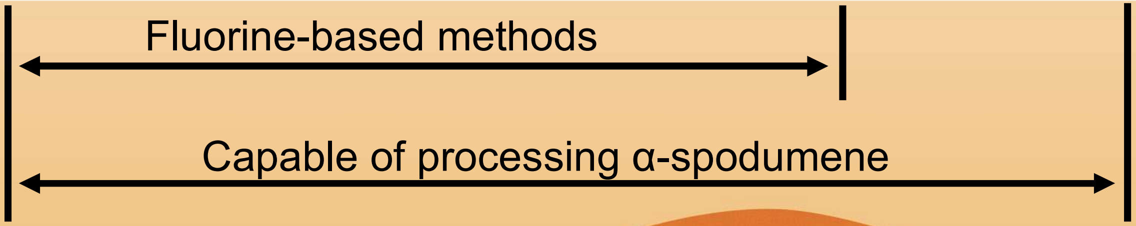
- Proven effective to β-spodumene, lepidolite and zinnwaldite;
- No considerable Na_2SO_4 problem
- Salt options:
  - Sulphate: K_2SO_4, **Na_2SO_4**, $FeSO_4$
  - Chloride: $CaCl_2$, NH_4Cl, NaCl
    - ✓ Capable of directly producing LiCl product
  - Carbonate: Na_2CO_3, $CaCO_3$
    - ✓ Followed by carbonation (CO_2) or conversion leaching (*e.g.* $Ca(OH)_2$);
  - Mixture of any above
- Fluorine may form fluorite (CaF_2) and/or Ca-Si-F compound ($Ca_4Si_2O_7F_2$), reporting to

Future research/trends

- Spodumene: still the main mineral source of lithium
    - Modification/improvement of H_2SO_4 method;
    - Direct treatment of natural spodumene;
    - Direct production of LiOH;
- Fluorine-based methods
    - Treatment of fluorine-containing waste;
    - Recycling/reuse of fluorine;
    - Indirect use of HF;
    - Reaction mechanism, equipment design, safety control.
- Towards comprehensive utilization - K, Al, Rb, Cs, F
    - Utilization of voluminous residue, *esp*. Al-Si based residue in the case of ion-exchange;
    - The key to compete with spodumene for lepidolite.

Lithium recovery from spodumene

	Acid method				**Alkali method**	
Major reagent	H_2SO_4	HF	H_2SO_4+HF	CaF_2+ H_2SO_4	NaOH	CaO/ $Ca(OH)_2$
Way of processing	Roasting	Leaching	Leaching	Leaching	Roasting/ autoclaving	Autoclaving
Spodumene type processed	β-spodumene	α/β-sposumene	α-spodumene	α-spodumene	α-sposumene	β-spodumene
Temperature of processing	~250 ^{o}C	~130 ^{o}C/ 75 ^{o}C	100 ^{o}C	~230 ^{o}C	600 ^{o}C fusion/ 250 ^{o}C autoclaving	100-205 ^{o}C
Representative ref.	Conventional	Kuang et al., 2012; Rosales et al., 2014	Guo et al., 2017	Kuang et al., 2012; Griffith et al., 2018	Sugyeong, 2018; Xing et al., 2019;	Mcintosh, 1946



Fluorine-based methods

Capable of processing α-spodumene

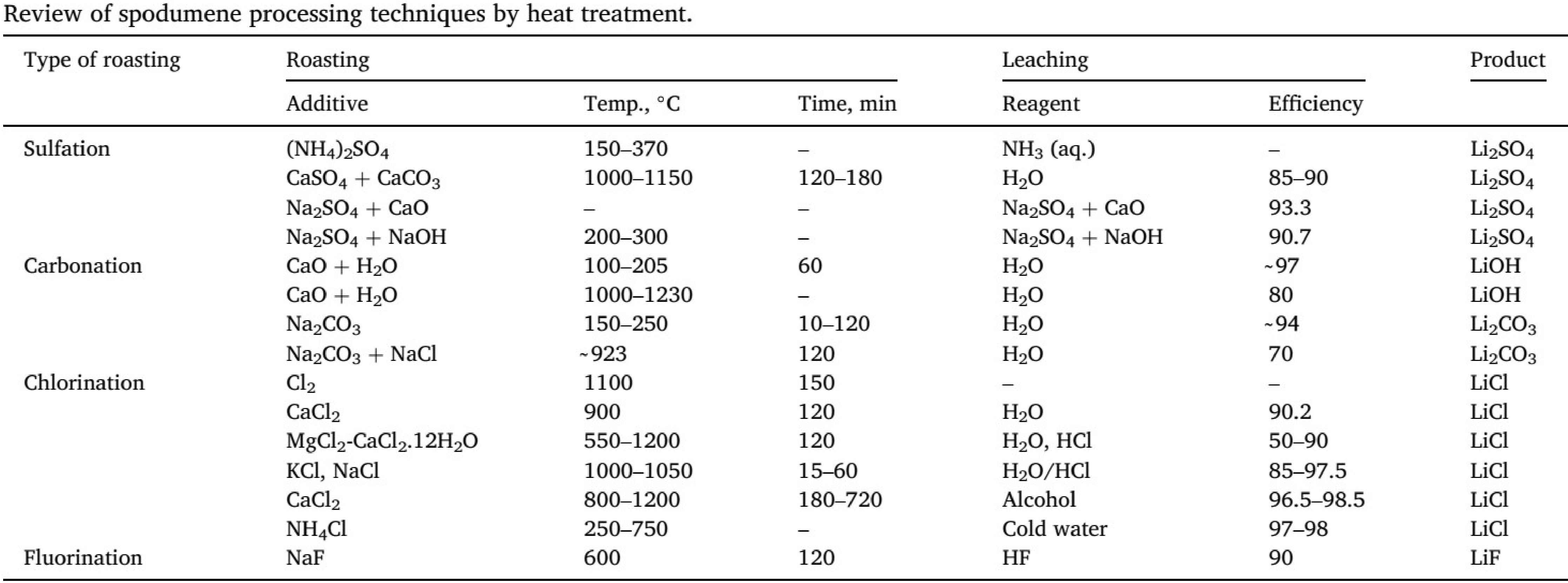
List of references

Lithium recovery from spodumene: High level approaches

	Sulphate method	Carbonate method	Chlorinating method	
Major reagent	K_2SO_4/ Na_2SO_4	Na_2CO_3/$CaCO_3$/ CO_2	Cl_2	$CaCl_2$/NH_4Cl/NaCl
Way of processing	Roasting/autoclaving	Autoclaving	Roasting	Roasting/autoclaving
Spodumene type processed	β-Spodumene	β-Spodumene	β-Spodumene	β-Spodumene
Processing Temperature	~1150 ^{o}C roasting/ 230 ^{o}C autoclaving	200-225 ^{o}C	1100 ^{o}C	900 ^{o}C roasting/ ~250 ^{o}C autoclaving 1000 ^{o}C roasting, H_2O leach
Representative ref.	Zeelikman et al., 1966; Kuang et al., 2018	Chen et al., 2011; Tiihonen et al., 2019 Haynes, B. & Mann, J., 2017	Barbosa et al., 2014	Gabra et al., 1975; Barbosa et al., 2015 Fosu et al

List of references

Lithium recovery from spodumene: Alternative Thermal Treatments

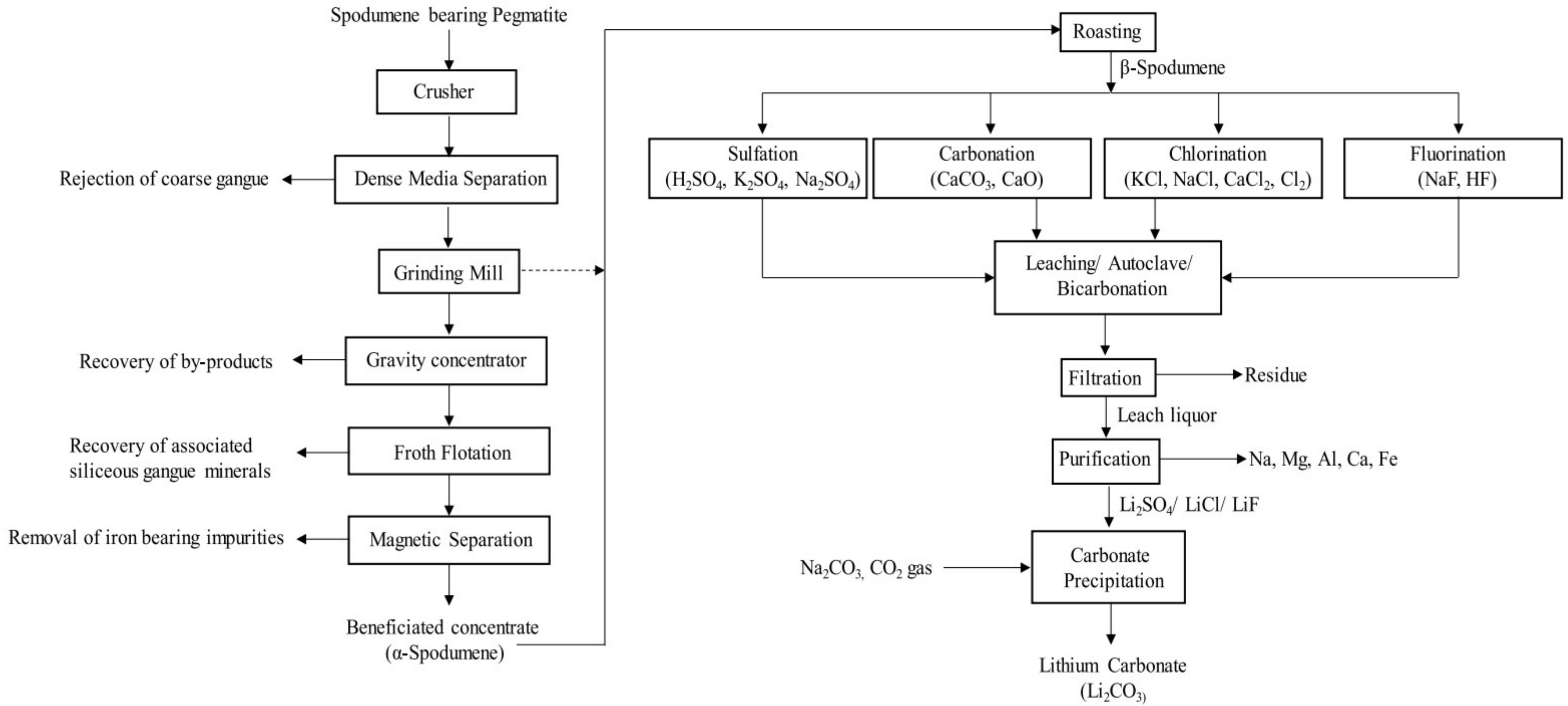


Review of spodumene processing techniques by heat treatment.

Type of roasting	Roasting			Leaching		Product
	Additive	Temp., °C	Time, min	Reagent	Efficiency	
Sulfation	$(NH_4)_2SO_4$	150–370	–	NH_3 (aq.)	–	Li_2SO_4
	$CaSO_4 + CaCO_3$	1000–1150	120–180	H_2O	85–90	Li_2SO_4
	$Na_2SO_4 + CaO$	–	–	$Na_2SO_4 + CaO$	93.3	Li_2SO_4
	$Na_2SO_4 + NaOH$	200–300	–	$Na_2SO_4 + NaOH$	90.7	Li_2SO_4
Carbonation	$CaO + H_2O$	100–205	60	H_2O	~97	LiOH
	$CaO + H_2O$	1000–1230	–	H_2O	80	LiOH
	Na_2CO_3	150–250	10–120	H_2O	~94	Li_2CO_3
	$Na_2CO_3 + NaCl$	~923	120	H_2O	70	Li_2CO_3
Chlorination	Cl_2	1100	150	–	–	LiCl
	$CaCl_2$	900	120	H_2O	90.2	LiCl
	$MgCl_2$-$CaCl_2.12H_2O$	550–1200	120	H_2O, HCl	50–90	LiCl
	KCl, NaCl	1000–1050	15–60	H_2O/HCl	85–97.5	LiCl
	$CaCl_2$	800–1200	180–720	Alcohol	96.5–98.5	LiCl
	NH_4Cl	250–750	–	Cold water	97–98	LiCl
Fluorination	NaF	600	120	HF	90	LiF

Kundu, T., et al., 2023, Powder Technology 415 (2023) 118142

Lithium recovery from spodumene: Generalized Flowsheets



Spodumene bearing Pegmatite

Crusher

Dense Media Separation

Rejection of coarse gangue

Grinding Mill

Gravity concentrator

Recovery of by-products

Froth Flotation

Recovery of associated siliceous gangue minerals

Magnetic Separation

Removal of iron bearing impurities

Beneficiated concentrate (α-Spodumene)

Roasting

β-Spodumene

Sulfation (H_2SO_4, K_2SO_4, Na_2SO_4)

Carbonation ($CaCO_3$, CaO)

Chlorination (KCl, NaCl, $CaCl_2$, Cl_2)

Fluorination (NaF, HF)

Leaching/ Autoclave/ Bicarbonation

Filtration

Residue

Leach liquor

Purification

Na, Mg, Al, Ca, Fe

Li_2SO_4/ LiCl/ LiF

Na_2CO_3, CO_2 gas

Carbonate Precipitation

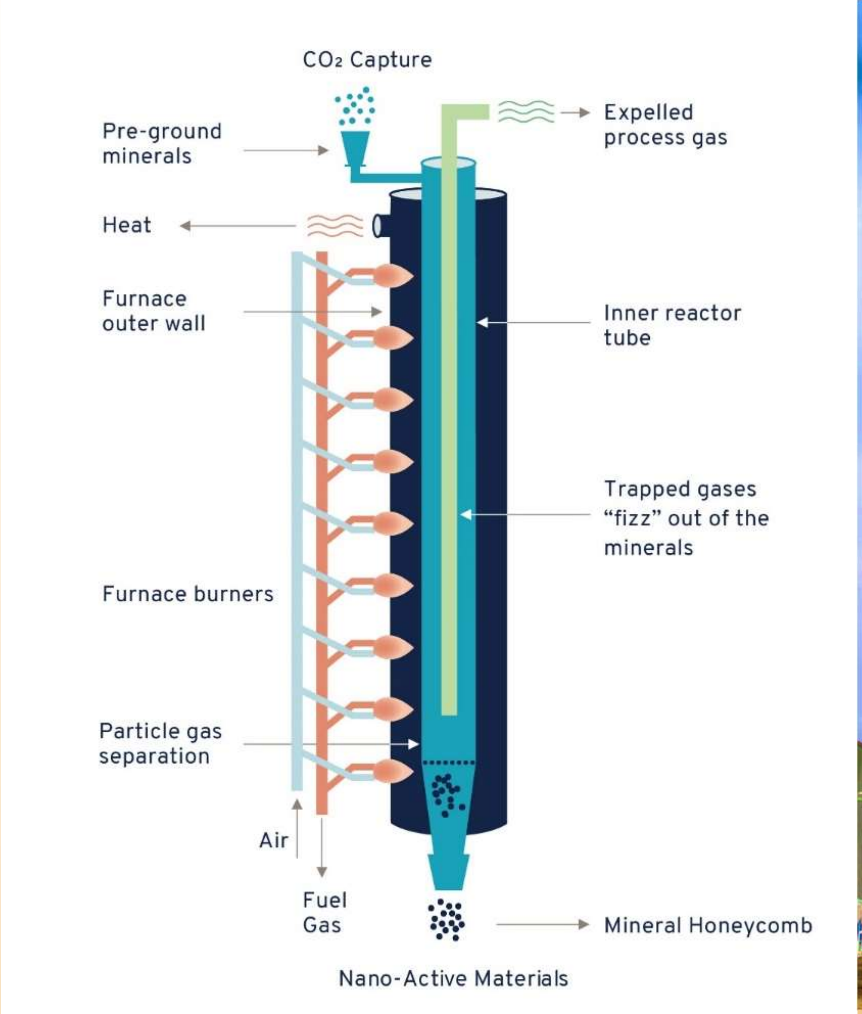
Lithium Carbonate (Li_2CO_3)

Kundu, T., et al., 2023, Powder Technology 415,118142

Lithium: Towards decarbonization of concentrating and refining (beyond “Electrify Everything”)

- Crushing & grinding in the concentrator are major energy consumers:
  - Significantly improving metallurgical recovery leads to less valuable material going to tailings that have been blasted, hauled, crushed & milled and significantly lowers the energy input per ton of metal unit that leaves the mine gate
  - However, better separation normally requires better liberation that is obtained at finer grinds
- Increasing mica contamination leads to surface fusion i.e., sintering and poor spodumene conversion. I.e., calcination energy is wasted as, no matter the energy input, the target conversion is not obtained
- Increasing fines lead to increasing elutriation losses, particularly where fuels and combustion gases increase gas flow
- At 1100 ºC, radiation heat transfer is the dominant heat transfer mode (compared to conduction & convection)
- Particle-particle and particle-gas contact play a less dominant role
- The more particle-particle contact occurs (number of particles and duration of contact), the higher the opportunity for sintering and clinkering
- Rotary kilns, originally developed for lower value limestone and cement may not be fit for purpose for spodumene that trades around $7,000 - $8,000 per tonne. Rotary kilns increases particle-particle contact and the opportunity for sintering & clinkering. Combustion gases leads to fines elutriation and reprocessing
- *Vertical flash calcination* with indirect heating eliminates most of these challenges, allowing integration of mineralogy and metallurgical knowledge with concentrator-to-refinery optimization based on a different equipment design, thereby minimizing sintering, maximizing conversion and minimizing fines elutriation and reprocessing, leading to significant better energy utilization to achieve conversion

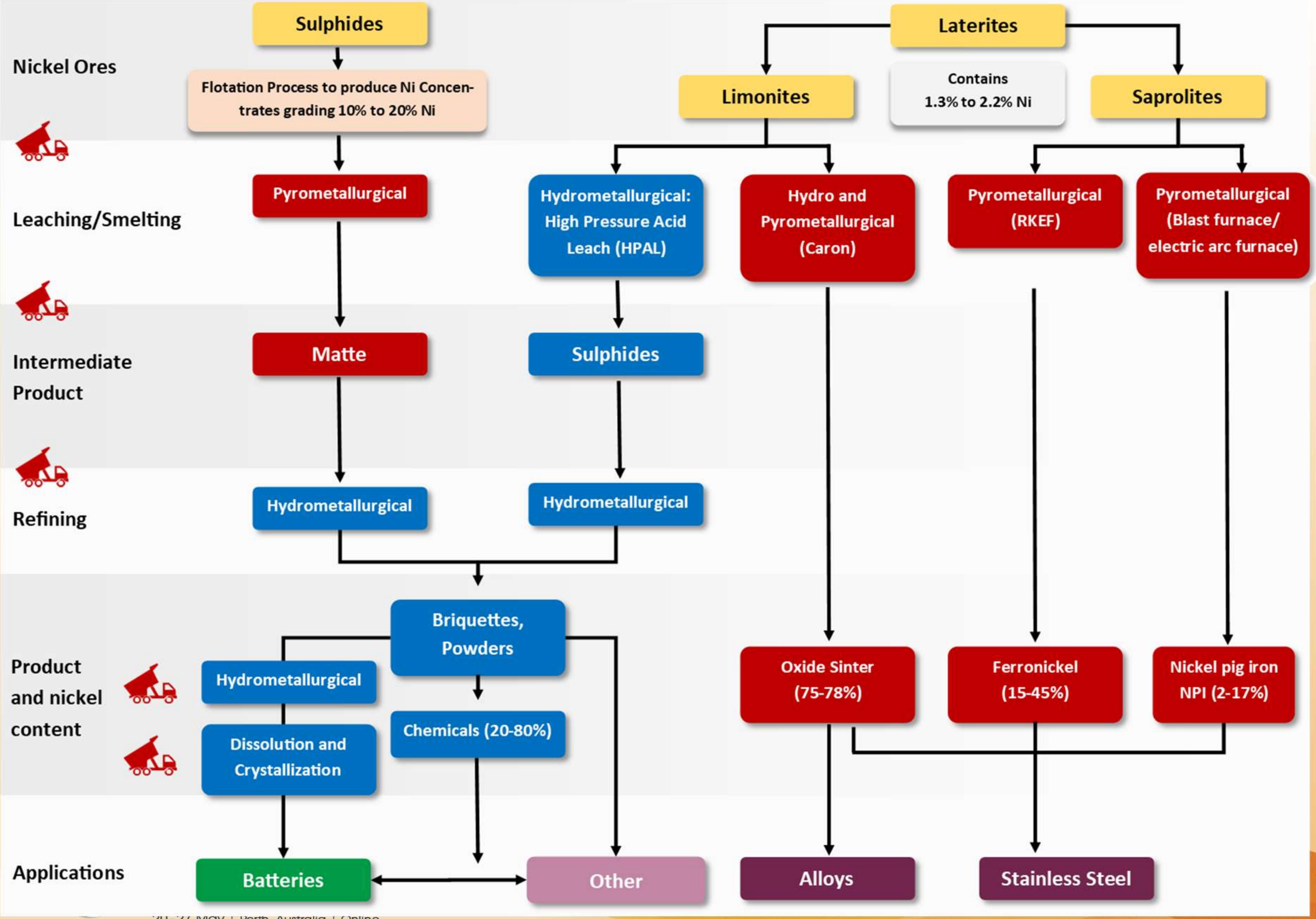
Vertical Flash Calcination Technology (Calix Ltd, Australia)



- Sector/stage-wise heating – thermal profile control
- Can be fully electrified
- Ideal for finer particles (<200 micrometre)
- Longer residence time due to serpentine particle movement rather than straight drop.
- Thermophoresis is used to move particles with thermal gradients. It leads to particles moving away from shot side-walls.
- No combustion gases in calcination zone (minimise particle elutriation)
- Elimination of clinkering
- Allows processing of fines

Nickel from Disseminated Sulfide Ultramafic Resources

CONVENTIONAL Ni PROCESSING OPTIONS



Nickel Ores

Sulphides

Flotation Process to produce Ni Concentrates grading 10% to 20% Ni

Laterites

Contains 1.3% to 2.2% Ni

Limonites

Saprolites

Leaching/Smelting

Pyrometallurgical

Hydrometallurgical: High Pressure Acid Leach (HPAL)

Hydro and Pyrometallurgical (Caron)

Pyrometallurgical (RKEF)

Pyrometallurgical (Blast furnace/ electric arc furnace)

Intermediate Product

Matte

Sulphides

Refining

Hydrometallurgical

Hydrometallurgical

Product and nickel content

Briquettes, Powders

Hydrometallurgical

Dissolution and Crystallization

Chemicals (20-80%)

Oxide Sinter (75-78%)

Ferronickel (15-45%)

Nickel pig iron NPI (2-17%)

Applications

Batteries

Other

Alloys

Stainless Steel

Schmidt, Buchert, Schebek, 2016. Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling, 112: 107-122

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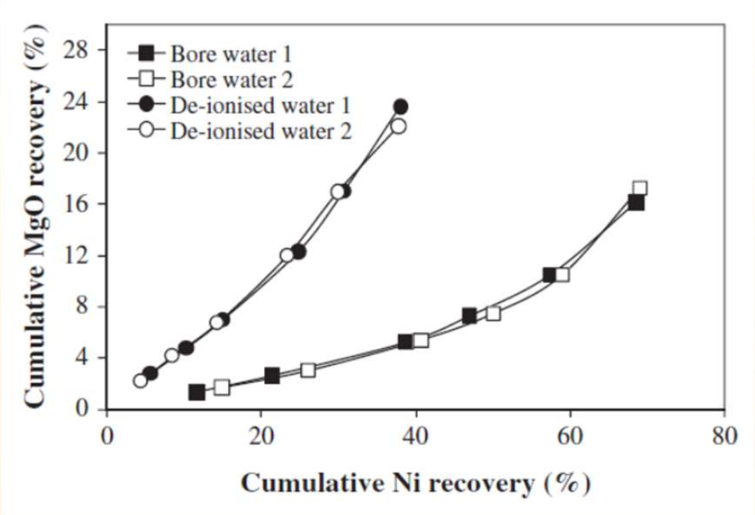
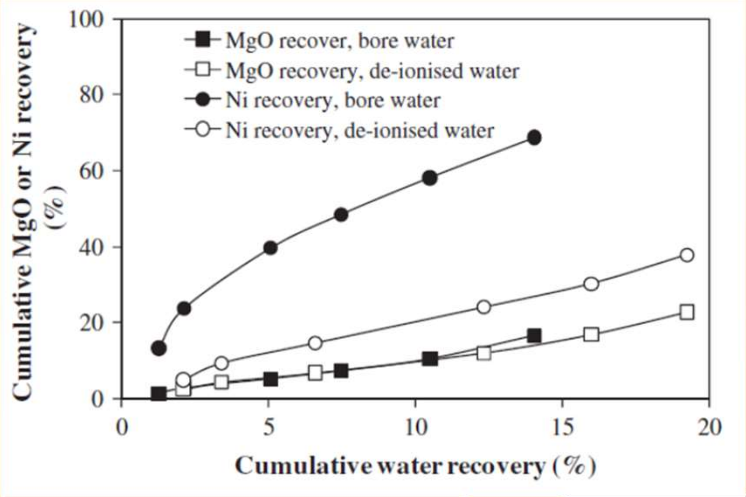
Nickel: Cutting the carbon footprint in nickel production (for disseminated sulfide resources)

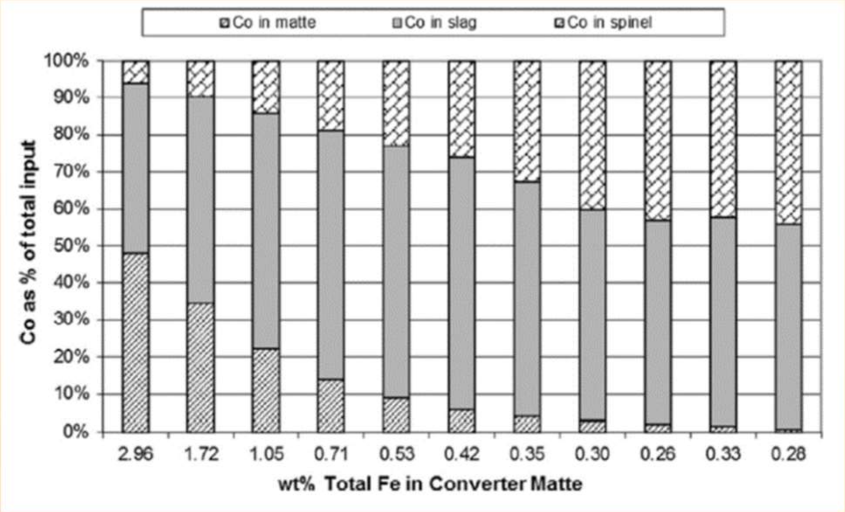
- Nickel extraction, concentrating and refining ⇨ large carbon footprint.
- WA Ni ores, particularly disseminated sulfides derived from ultramafic deposits are interlocked in gangue minerals high in magnesium and iron which both pose challenges in the smelter furnaces and converters
- Concentrate grade constraints by the smelter lead to very high losses of nickel and cobalt to tailings (40-50%).
- A direct leach & recovery technology using mildly alkaline glycine solutions was developed at Curtin University. This allowed the following outcomes:
  - Direct leaching of nickel and cobalt from rougher concentrates, fines, slimes, ores and tailings possible, nearly doubling saleable metal units for the same energy input during comminution & mining
  - Selectivity improved as insignificant iron and magnesium was dissolved
  - As metal sulfates rather than metallic nickel was required, it provided a direct hydrometallurgical pathway to battery chemicals
  - Carbonation of magnesium-rich ores and tailings is a fitting technology as the alkaline environment doesn’t lead to decomposition of carbonate minerals, leading to permanent sequestration of CO@ from point sources
  - Glycine, a non-toxic, cheap reagent that is recovered and recycled in the process, is deployed
  - The GlyLeach™ process is currently being optimized and is due to be piloted in the coming two years.
- This is an example of how knowledge of mineralogy, novel chemistry and process flowsheet design can lead to significant decarbonization while achieving other sustainability and metallurgical objectives

Ni and Co losses in conventional processing of disseminated sulfides

- MgO (slag liquidus, viscosity impact) and FeS (matte aisle logistics) specification in smelters constrains nickel and cobalt recovery at concentrator.
- Large Co losses occur during matte converting that are hard to recover.
- Cleaner tails still contain high amounts of ground sulfide that is an environmental problem.







*Cobalt loss to matte is for a PGM-Ni-matte in P-S Converter.

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Some of the hurdles

Conventional processing of nickel resources is accompanied with many metallurgical challenges:

- Aggressive non-recyclable reagents
- Often poor flotation recoveries to meet smeltable concentrate specifications
- High temperature (ferronickel / nickel pig iron) or high pressure (HPAL) approaches required
- Poor cobalt recoveries, particularly for smelting & converting routes
- Reagents are typically not recycled and reused leading to poor circularity of materials
- Exotic materials of construction required, particularly for HPAL
- Poor ability to recover associated precious metals (e.g., Au, Pt, Pd), and poor payabilities
- Significant "smearing" of contaminants across the extraction and refining, e.g., Fe, Mn, Mg, Cr, Al, Si, As, Se, and Te
- Complicated multistage extraction routes, often better targeted towards metallic nickel production for the stainless-steel market or crude MHP production.

Towards “Green” Nickel and Cobalt - Process Requirements:

- Lead to significantly higher recoveries of Ni & Co
    - Given the carbon footprint of the mining operations and comminution circuits, lost Ni translates directly into a large carbon penalty
- Use environmentally friendlier reagents, and reagents that are less corrosive
- Allow the reprocessing of tailings, including pyrrhotite tailings and allow processing of ores and concentrates
- Bypass the requirement for smelting and converting, or pressure leaching or pressure reduction to metallic nickel
- Sidestep any route that requires intermediate, MHP, MSP, matte and metallic Ni production to produce Ni & Co sulfates directly
- Eliminate contaminants such as Fe, Mg, As, Se, SiO2, $Al_xSi_yO_z$ as early as possible in the process without “smearing” them across multiple process steps.
    - Every unwanted element not eliminated at the start leads to recovery losses later

Attributes of the alkaline glycine process

Reagent is non-toxic	Reagent recovery and reuse is easy and cost-effective	It can be operated under dilute and concentrated modes
It is environmentally benign	The reagent cost is low (< AUD 2000/tonne)	It is chemically stable under alkaline conditions (compared to cyanide, thiosulfate, etc.)
It has a high affinity for: Ni, Co, Cu, Au, Ag, Pd, Pt, Zn, Pb, Cd	It can be used synergistic with cyanide (for precious metals)	The precious metal glycinate complexes adsorb well onto activate carbon
Given the alkaline operation, there is no or very limited interaction with acid consuming materials	It can be applied in various leach modes (such as heap, in-situ, vat and agitated tank leaching)	The alkaline operation allows low cost materials of construction
Highly soluble, but non-hygroscopic crystals	No transportability & logistics, trade restrictions	Ease of base metals removal / recovery
Thermally stable	Non-volatile	Simple chemistry
Insignificant Fe, Mn, Mg, Si, Al, Cr dissolution (excellent gangue rejection)	Cu- glycinate is a good oxidant	No pH changes required between base and precious metals leaching stages

Leach evaluations on different nickel-bearing materials: LG concentrate, Ores, Tailings & Slimes

Alkaline glycine leach extractions of ores, tailings and concentrates

Alkaline Glycine leach extractions were performed at:

- Room Temperature
- Atmospheric Pressure
- Controlled dissolved oxygen levels / Redox
- Controlled (maintained) pH
- Results reflect outcomes of batch tests
- Resin-in-pulp / resin-in-leach and counter-current transfer can further improve results
- Different alkalizing agents used, depending on nature of material treated

Sample	Rougher concentrate 1	Rougher concentrate 2	Ore 1	Ore2	Cleaner Tails 1	Cleaner Tails2	High Pyrrhotite slimes
Ni	6.13	6.02	0.78	1.67	0.886	0.79	4.075
Fe	9.12	33.5	5.89	11.4	5.24	6.43	26.50
Ca	0.49	0.33	0.55	1.49	0.39	0.20	2.975
Mg	16.29	4.04	22.9	5.92	22.25	22.2	4.465
S	6.04	27.6	0.83	7.04	1.15	1.70	15.30
Mn	0.08	0.09	0.05	0.11	0.06	0.06	0.120
Co	0.11	0.179	0.014	0.048	0.021	0.019	0.132
Zn	0.03	0.012	0.008	0.011	0.001	.023	0.021
As	0.03	0.007	0.007	0.005	0.0045	.007	BDL
Cu	0.29	0.301	0.13	0.10	0.0185	0.215	2.00

Test ID	Rougher Concentrate 1	Rougher Concentrate 2	Ore 1	Ore 2	Cleaner Tailings 1	Cleaner Tailings 2	High pyrrhotite Slimes
Solid, %	30	10	40	30	30	30	10
Initial pH	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Gly:Ni mole ratio	4:1	4:1	4:1	4:1	4:1	4:1	4:1
Residence time, hours	72	72	48	72	48	48	72
Ni Extraction, % of total Ni	90.2	81.9	69.1	74.8	62.5	80.1	81.5
Co Extraction, % of total Co	85.7	16.5	65.3	27.5	64.5	72.6	71.9

The leachates obtained showed high selectivity of Ni and Co over Fe, Mg, As, Ca, Mn.

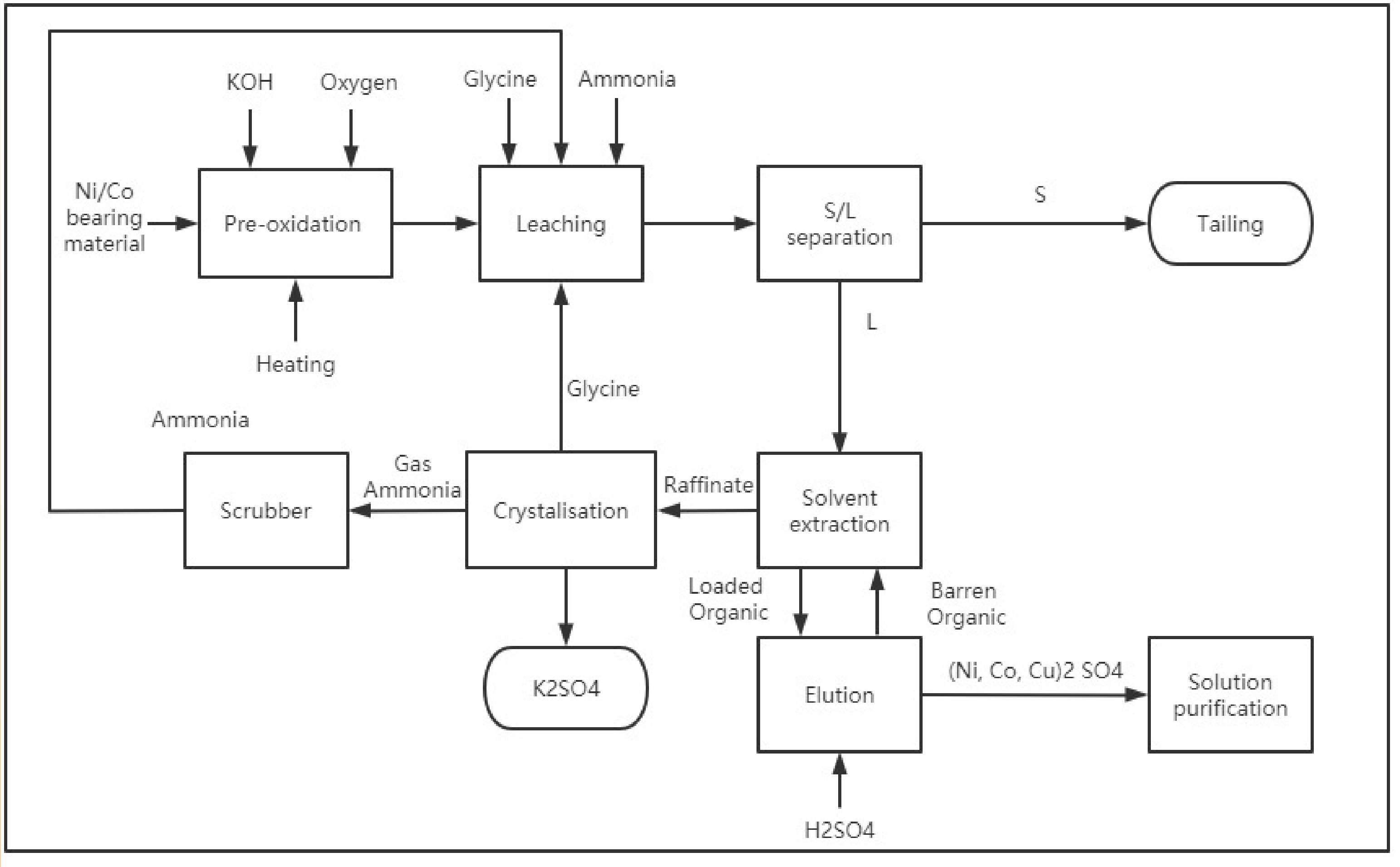
Test ID	Element	Ni	Co	Fe	Ca	Mg	S	Mn	Zn	As	Cu
Cleaner Tails 1	Final solution assay, mg/L	2070	52.8	BDL	118	79.8	3200	BDL	0.8	BDL	48.8
Cleaner Tails 2	Final solution assay, mg/L	2805	63.8	1.5	30.5	25.3	3860	BDL	11.0	BDL	118
High pyrrhotite Slimes	Final solution assay, mg/L	3500	100	19.6	12.8	7.4	3770	BDL	BDL	BDL	646
Ore 1	Final solution assay, mg/L	4100	80.5	BDL	50.6	36.5	4820	BDL	2.5	BDL	318
Ore 2	Final solution assay, mg/L	4020	27.2	11	78.6	78.4	7760	BDL	9.0	0.11	213
Rougher Concentrate 1	Final solution assay, mg/L	7560	147	3.4	10.8	22.4	9860	DBL	15.8	0.07	316
Rougher Concentrate 2	Final solution assay, mg/L	5080	30.8	115	5.5	2.6	9750	BDL	0.4	0.21	169

- Cobalt leaching mostly congruent with nickel leaching
- Silica levels BDL (not shown)
- Sulfur leaching congruent with nickel leaching
- BDL: Below detection limit (by ICP OES)

Metal recovery from solution, reagent recycle and metal separation:

- Glycine leachates are recovered from solids using filtration
- Excellent primary extraction of Ni, Co, and Cu is possible with either:
  - Ion exchange resin (for leachates from ores and tailings)
  - Solvent extraction (for leachates from concentrates)
  - Metal recovery onto resin or to SX extractant is as the divalent cation
  - Glycine remains in the barren raffinate and is recycled (with sulfate) back to leach
  - Ni, Co and Cu are stripped from resin or SX extractant using sulfuric acid
  - Ni, Co and Cu sulfates are separated in acidic sulfate medium using conventional solvent extraction technologies (e.g. Cyanex 272 for Ni-Co separation)
  - Final pure nickel sulfate, cobalt sulfate and copper sulfate can be crystallised, or transferred (minus copper) for mixed hydroxide cathode precursor manufacture
- Dissolved sulfate can be removed and differentially crystallised as the sulfates of any of K, Na, NH_4^+ or Ca

Option 1 (for Concentrates and high sulfide materials): GlyAmm based



Conclusions:

Alkaline glycine technology provides an ideal pathway to produce “Green” nickel and cobalt

- It allows maximum recovery of nickel and cobalt with minimal co-extraction of impurities
- It allows pathways directly to nickel and cobalt sulfate without the need for smelting, converting, or pressure leaching
- It eliminates most of the typical problematic contaminants, such as iron, magnesium and manganese from the first extraction stage
- It operates under similar processing conditions, and with similar equipment to gold leaching circuits
- A detracting factor is leach residence time (around 24 hours) leading to more tankage
- Glycine recycle is simple, minimising reagent costs
- Processes can be used with saline water
- Applicable to various grades, but optimal for ores & concentrates with nickel grades of between 0.3% - 7.0% Ni
- Various alkalising agents can be considered (hydroxides of K, Na, NH_4^+, Ca, or carbonates of K, Na, NH_4^+)
- Good palladium recoveries can be obtained using GlyLeach™ / GlyCat ™, when associated with pentlandite

Towards better sustainability and decarbonization in mattery metal value chains

Decarbonization is achieved through:

- Novel process chemistry and process mineralogical understanding
  - E.g., glycine use in nickel processing
  - Mineral carbonation and CO_2 sequestration in nickel ore processing
- Maximizing recoveries and conversions through fit-for-purpose equipment design
  - E.g., indirectly heated vertical flash calcination of spodumene
- Maximizing recoveries through novel chemistry
- Simplifying across the whole value chain (e.g., mine, concentrator, pyrometallurgical conversion and refinery) and reviewing overall process integration, e.g.:
  - direct leaching of nickel to produce battery metals chemicals and
  - processes that allows fines processing in spodumene conversion

To ensure greater sustainability we have to:

- Increase processing efficiencies and recoveries
- Reuse and recycle reagents and water
- Use what nature provides us
- Electrify what we can with renewable sources & energy storage
- Maximize the use of non-toxic and benign reagents
- Understand the interactions between mineralogical and chemical properties and materials interactions (particle-particle and particle-gas) in equipment, and opportunities to unlock inter-business unit bottle necks