Technologies for Sustainable Mining and Refining

Facts & Figures – WMF 2024

JULY 11TH 2024

WORLD MATERIALS FORUM

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Purpose of the study: Identify the most promising technologies that could improve the environmental impact of mining and refining in the coming years

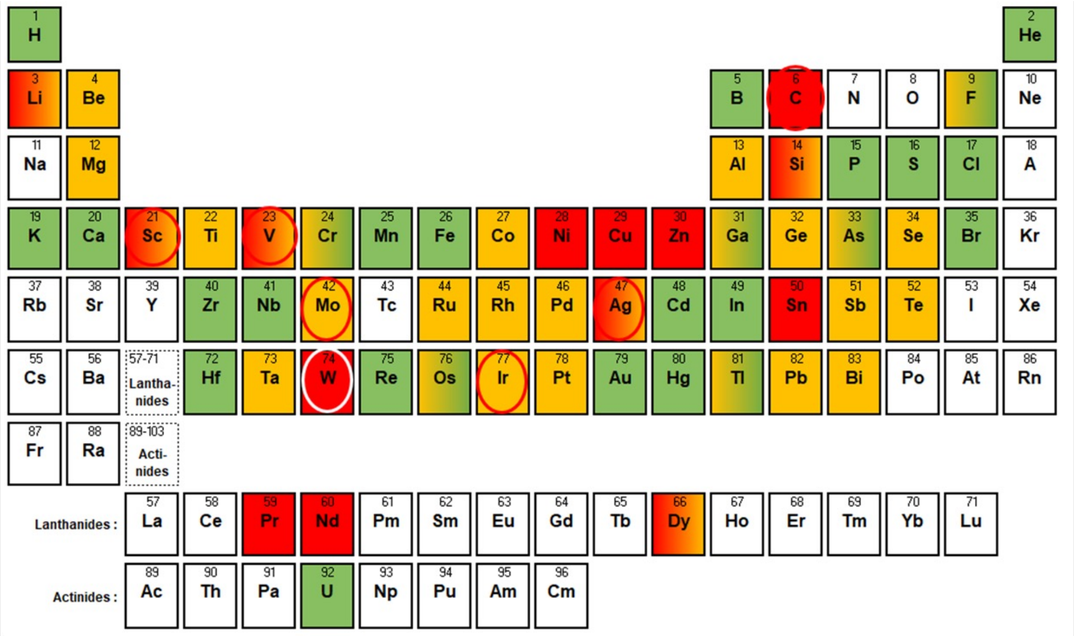
Identify the technologies that…

Environmental KPIs	… have a high impact on **reducing energy consumption, CO_2 emissions, water usage or waste in mining or refining** processes
Technology maturity	… are either existing best practices but only used by 1 or 2 players, or new technologies **with a TRL* superior or equal to 4** (Proof of Concept completed)
Selected critical materials	… are related to selected critical materials: **Copper, Nickel, REE (Praseodymium, Neodymium) and Lithium**

Note: (*) Technology Readiness Level
Source: Arthur D. Little

Ni, Cu, Pr, Nd, Li are some of the most critical materials in terms of environmental impact

2024 Criticality Assessment WMF



More critical in 2024: 6 elements –**High-purity Graphite (C), Tungsten,** Sc, V, Ag, Mo

Less critical in 2024: None

Red elements combine:

- Role in electrification & energy transition
- Long term uncertainties
- Short term supply chain bottlenecks
- Limited substitution possibilities

- Very high degree of risk
- High probability of risk occurrence
- Risk of occurrence to be closely monitored
- Low probability of risk occurrence
- Low degree of risk

Elements in Scope

Five of the most critical elements, especially for electrification, are selected within the scope of our study

28 Ni — Nickel (Class 1)

29 Cu — Copper

Rare-Earth Elements (REE)

59 Pr — Praseodymium

60 Nd — Neodymium

3 Li — Lithium

Source: 2024 Criticality Assessment results by BRGM, CRU & McKinsey

While mature technologies exist to reduce CO_2 emissions and water usage, new technologies are needed for reducing energy consumption and production of waste

		Current production Process	Production Volume	Environmental impact: Energy consumption	CO_2 Emissions: Energy	CO_2 Emissions: Process	Freshwater consumption**	Waste
			kt metal, 2021	*GJ/t metal*	*tCO_2/t metal*		*m^3/t metal*	*t/t metal*
Ni (Class 1)		Pyrometallurgy from Sulphide	789	114	9	0	68	65
		Hydrometallurgy from Laterite (HPAL)	197	194	12	8	303	351
Cu		Pyrometallurgy from Sulfide	17,000	65	5	0.1	91	96
		Hydrometallurgy from Oxide	4,000	35	2	0	70	125
REE	Pr	Hydrometallurgy from mixed Oxide	11	510	17	2†	114	10,870
	Nd		35	419	16	2†	89	2,440
Li		Brine Process	256*	62*	1*	2*	23*	24*
		Hard Rock Process	319*	203*	19*	2*	76*	34*

Energy emissions can be reduced by using green energy

Freshwater consumption can be reduced by recycling water

High	201~
Medium	51~200
Low	1~50

Note: (*) Tonnage metal indicates tonnage of Lithium Carbonate (LCE), not that of Lithium metal; (**) Freshwater consumption does not take into account recycled water; (†) High level estimation

Sources: IEA, CSIRO, Eurometaux, Journal of Cleaner Production (Norgate, 2007), CDA (Dresher, 2001), Hindawi (Koltun, 2014), Argonne, Arthur D. Little analysis

We have selected 10 breakthrough technologies for ultra-low Mining Footprint

Scope	Element	#	Technology	Environmental impact (Relative to incumbent process): Energy	Emission	Water	Waste	TRL	Applicability	CAPEX* ($/tpa)	OPEX** ($/t)	Major Players
Transverse		1	AI Resource imaging	-15%	-15%	0%	-50%	8	No major limitation	Marginal	Savings on a case-by-case basis	GoldSpot Discoveries Corp., Sensore, Computational Geosciences
Transverse		2	Dry stack tailings	+10%	0%	-75%	-10%	9	No major limitation	Comparable to incumbent	200-600	MP Materials, Metso, FLSmidth, Takraf, Delkor
Transverse		3	Efficient rock grinding	-80%	-50%	0%	0%	4	No major limitation	Comparable to incumbent	-25% of incumbent	i-Pulse
Specific to elements	Ni	4	Nickel sulfide pressure oxidation	-10%	-50%	+100%	-15%	8	No major limitation	60k	11k	Vale
Specific to elements	Ni	5	Nickel rock bioleaching	-50%	-65%	+350%	-15%	8	Bio compatibility	21k	10k	Finnish Minerals Group Suomen Malmijalostus, EVNi
Specific to elements	Cu	6	Copper in-situ leaching	-50%	-50%	-70%	-95%	8	Well-fractured rocks	4k	4k	Taseko, Excelsior Mining Corp, Enviro Copper
Specific to elements	Cu	7	Copper sulfide leaching	-50%	-50%	-50%	-95%	8	No major limitation	40k	3k	Jetti, Nuton, Cycladex
Specific to elements	REE (Pr, Nd)	8	REE Efficient Separation	-15%	-10%	-5%	0%	6	No major limitation	5k	8-16k	USA Rare Earth, REEtec, ucore, 中国五矿集团公司 China Minmetals Corporation
Specific to elements	Li	9	Direct Lithium extraction	-25%	-10%	+200%	-90%	8	Sufficient conc. of Li	32k†	3k†	Lilac, Standard Lithium, Summit Nanotech
Specific to elements	Li	10	Lithium un-calcinated rock leaching	-60%	-60%	-85%	-85%	6	No major limitation	21k††	2-4k††	Cycladex, Lithium Australia

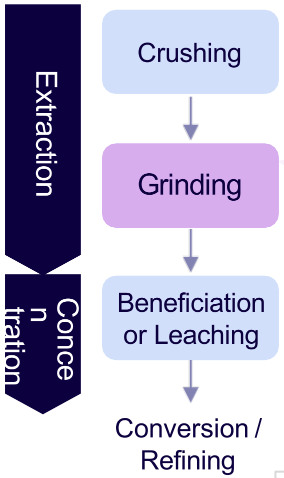
Note: (*) Sum of CAPEX divided by tones of metal per year. Figures show typical values but highly depend on deposit quality; (**) USD per ton of metal; Transverse: indicates additional OPEX by deploying technology; Specific to elements: OPEX of whole process by replacing existing technology. Figures show typical values but highly depend on deposit quality; (†) USD/ton LiOH・H_2O; (††) USD/ton Lithium Carbonate (LCE),
Sources: Arthur D. Little analysis

Strong positive impact — Strong negative impact

Illustration #1 : Efficient rock grinding could save up to 80% in energy consumption

Technology #3 Efficient rock crushing

Pulsed power generator for breaking down rocks using a large dose of plasma physics



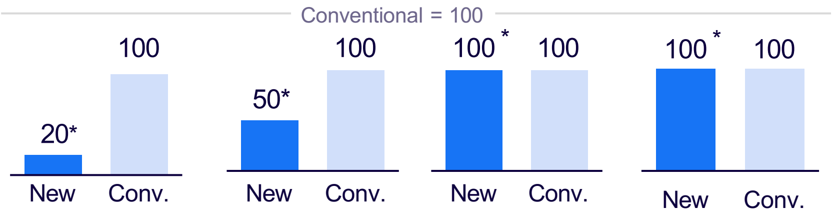
Pulsed power offers the potential to revolutionize the process of grinding mineral ore by using electrical arcs to burst rock from the inside, instead of crushing from the outside. Grinding rock is estimated to make up around 25% of the total energy at an average mine site and consume 3-5% of global electrical energy. This equates to ~600Mt CO2e, offering immense potential for emissions abatement through energy efficiency

Step which concerns new technology

Benefits	• Higher mineral liberation enhances downstream recovery • Less energy is required when rocks burst from the inside, rather than crushing them from the outside
Industrial challenges	• Technology yet to be widely proven at an industrial scale (TRL4)

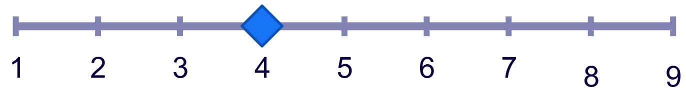
Environmental impact

Energy Consumption	Emissions	Freshwater Consumption	Waste



50% reduction of crushing energy	Link with energy	Water not involved	No change

TRL



- Lab PoC complete
- Commercial operation in 3-4 years

Major Players

CAPEX	Comparable to conventional rock crushing process
OPEX	25% reduction of total opex

Note: * *Forecast reduction once technology is scaled-up*
Sources: I-Pulse, Arthur D. Little

Illustration #2 : Dry Stack Tailings allows reduction of water usage by up to 75%

Technology #2 Dry stack tailings

Dry stack tailings process enables reduction of the amount of water used

Thickening
- Tailings are dehydrated through increasing their density from very low solids to medium/high density (~65%)
- Liquid overflow is recycled back into the process through a closed loop

Filtering
- The thickened tailings are then dewatered even more through a filtering process, producing a filter cake
- Water extracted is again recycled

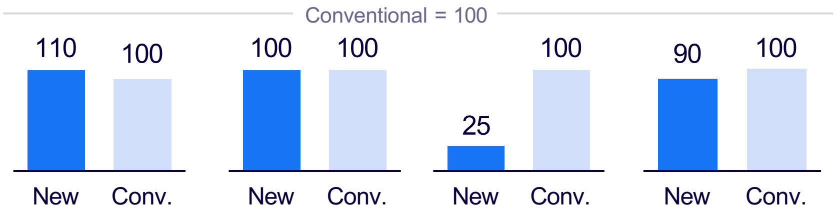
Dry material handling
- Dry tailings are then stored in an on-site lined impoundment (as opposed to a large tailings dam in conventional operations)

Step which concerns new technology

Benefits	• Reduced water consumption due to high recycling rates • Lower risk of environmental contamination, e.g., reduced leakage, dam breaks, groundwater contamination, methane emissions
Industrial challenges	• More energy intensive due to the dewatering process, leading to higher operating cost

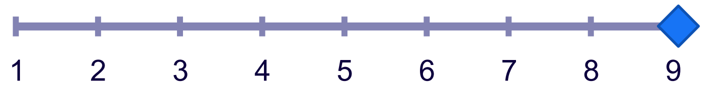
Environmental impact

Energy Consumption	Emissions	Freshwater Consumption	Waste



Energy Consumption	Emissions	Freshwater Consumption	Waste
More energy is required for the dewatering process	More energy-sensitive but counter balanced by lower risk of methane emissions	Tends to conserve more water because enables a larger portion to be recycled	Can often be more easily reclaimed

TRL



- Dry stack tailings are fully mature systems and have been proven to work in commercial setting with high reliability and effectiveness

Major Players

Equipment manufacturers: FLSmidth, Metso, TAKRAF

Users: DELKOR, MP Materials

CAPEX	Comparable to incumbent
OPEX	Additional 2 to 3.5$/T of tailing; 200-600$/T of metal

Sources: MP Materials, Arthur D. Little

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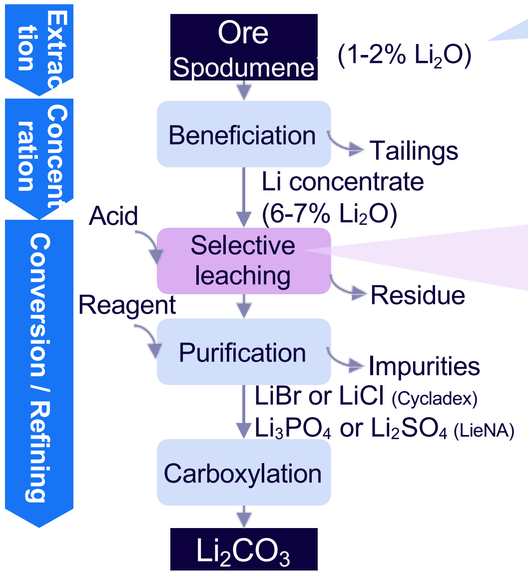
3 Li

Illustration #3 : Lithium leaching of uncalcinated rock allows up to 60% energy reduction and 85% waste reduction

Technology #10 Lithium Uncalcinated rock leaching

Efficient leaching of spodumene without calcination using chemical reagents



Wasted fine spodumene or tailings with low concentration of lithium could be processed without beneficiation step

1. Crushing/Grinding
2. Froth flotation

New technologies
- Cycladex: Unique leaching using Br or Cl chemistry
- LieNA process: HCl after caustic conversion

Enables the avoidance of the calcination step which consumes a substantial amount of energy

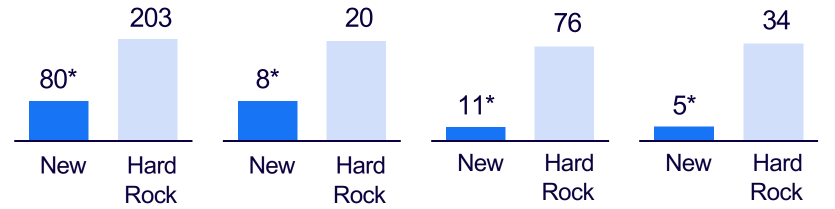
* Li_3PO_4 could be directly used to produce LFP battery cathode

Step involving new technology

Benefits	• Quick + mild leaching eliminate energy-intensive calcination • No need for a sulfuric acid plant (Use of Br or Cl chemistry) • Direct synthesis of Li3PO4 for battery use (LieNA process)
Industrial challenges	• Industrial scale yet to be tested

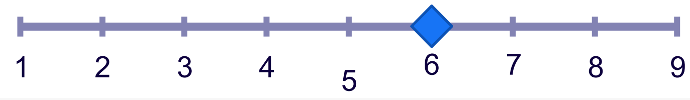
Environmental impact

Energy Consumption	Emissions	Freshwater Consumption	Waste
GJ/t LCE	t CO_2/t LCE	m³/t LCE	t/t LCE



Energy Consumption	Emissions	Freshwater Consumption	Waste
Less than hard rock due to no calcination	Less than hard rock due to no calcination	Much less consumption due to water recycling	No sulphate waste

TRL



- Cycladex: 100 tons scale operation running in Arizona, US
- LieNA process: Lithium Australia has started a pilot plant in Q3 2024 under a joint development agreement with Mineral resources

Major Players

CYCLADEX (Develops technology)

Lithium Australia (Develops LieNA process)

CAPEX

21 kUSD/t LCE
(vs 26 kUSD/t LCE for conventional hard rock process)

OPEX

2.2-3.5 kUSD/t LCE
(vs 4.4 kUSD/t LCE for conventional hard rock process)

Note: (*) High level estimation, waste can be used as a by-product in construction with limited cement addition (similar to steel slags)
Sources: Press search, Lithium Australia, Cycladex, Arthur D. Little analysis

Applying these new technologies would drastically lower down the environmental impact of mining and refining

	Current production Process	Energy consumption (GJ/t metal)	CO_2 Emissions (tCO_2/t metal)	Freshwater consumption ** (m^3/t metal)	Waste (t/t metal)
Ni (Class 1)	Pyrometallurgy from Sulfide	114	9	68	65
Cu	Pyrometallurgy from Sulfide	65	5.1	91	96
Cu	Hydrometallurgy from Oxide	35	2	70	125
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Li	Brine Process	62*	3*	23*	24*
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New production Process	Energy consumption (GJ/t metal)	CO_2 Emissions (tCO_2/t metal)	Freshwater consumption ** (m^3/t metal)	Waste (t/t metal)
Sulfide pressure oxidation	86	4	22	35
Nickel Ore bioleaching	46	2	77	32
Copper sulfide leaching	22	2	11	3
In-situ leaching	13	1	5	3
Hydrometallurgy (Sx-Ew) with efficient separation	346	16	28	6,850
Hydrometallurgy (Sx-Ew) with efficient separation	285	15	21	1,540
DLE	39	2	18	1
Uncalcinated rock leaching	77	7	3	3

Level	Range
High	201~
Medium	51~200
Low	1~50

Note: (*) Tonnage metal indicates tonnage of Lithium Carbonate (LCE), not that of Lithium metal; (**) Freshwater consumption does not take into account recycled water; (†) High level estimation
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