Unconventional Sources of Critical Minerals:

Opportunities for Recovery from Mined Materials in the Copper and Gold Environment

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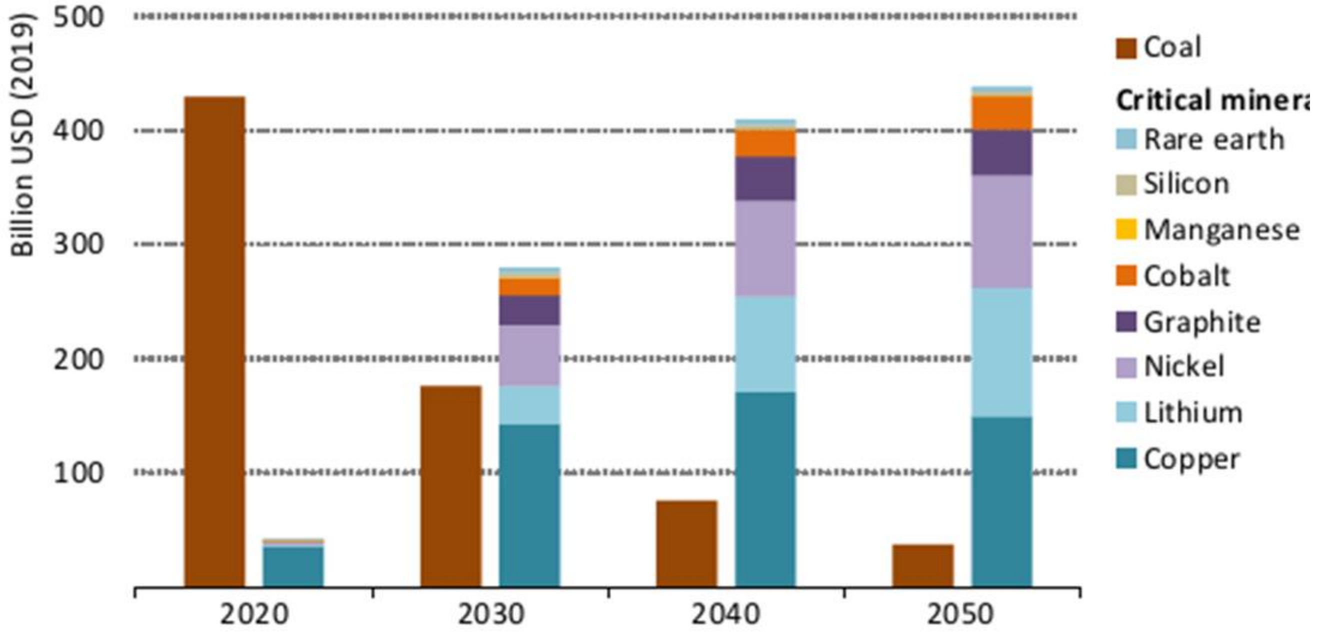
Introduction

Critical minerals are needed to enable the **energy transition** from fossil fuels to renewables, and for advanced technologies associated with **defense**, **computing**, and **communications**.



From: IEA, 2021

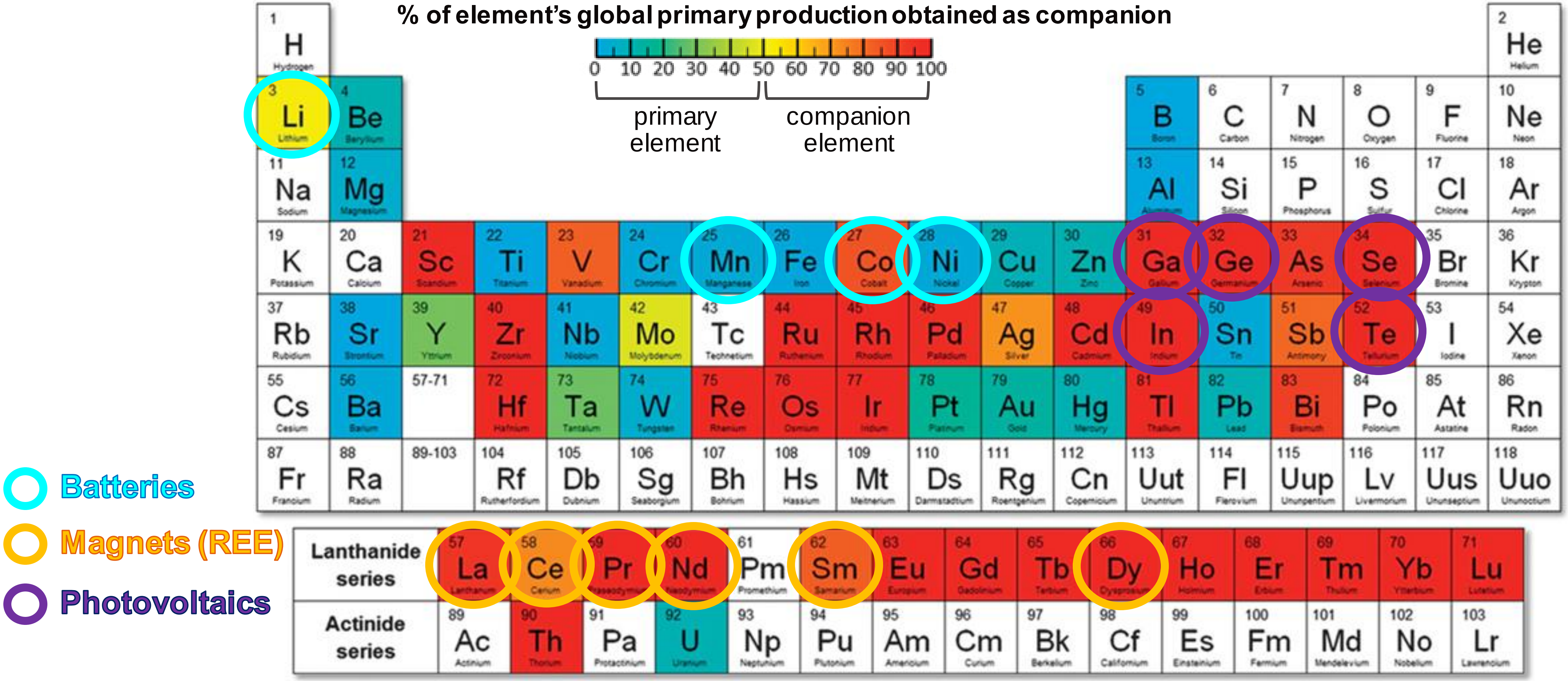
From: Nassar, USGS, 2020

Critical mineral demand in 15+ years is predicted to rise by orders of magnitude.

Key Challenge:

There is a gap in current supply of CM/REE compared to expected future demand.

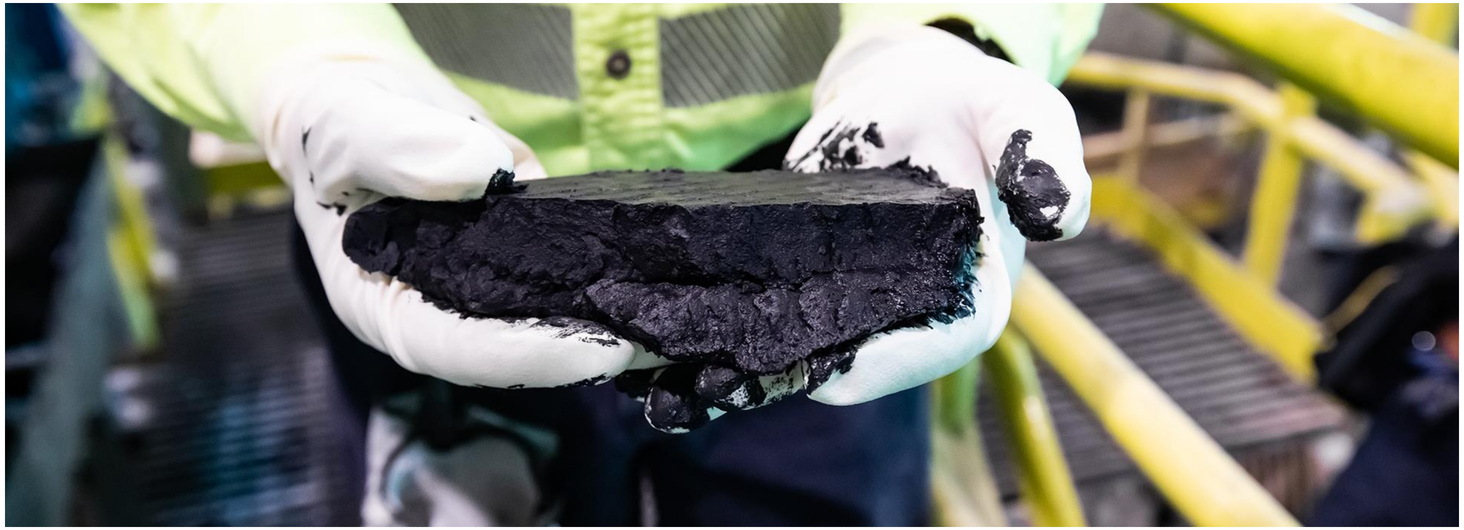
Many Critical Minerals Occur as Companion Elements

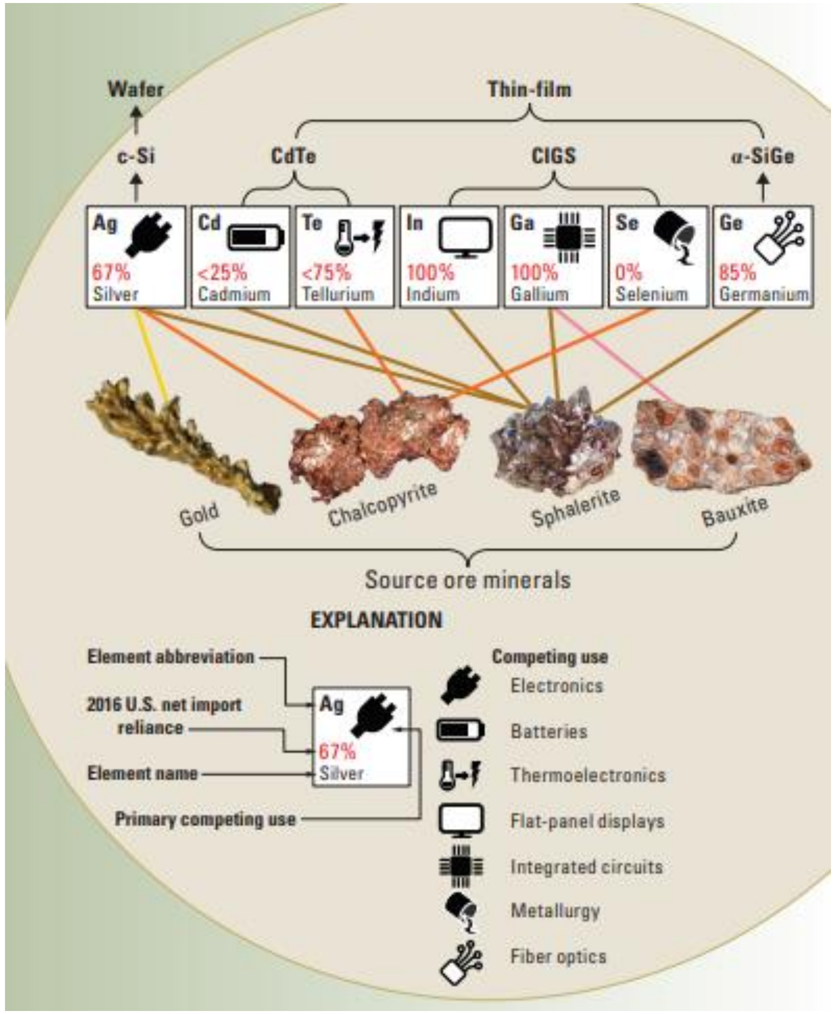


Nassar et al., USGS, 2015

Secondary Sources of Critical Minerals

- In the absences of available **primary sources** (**conventional resources, e.g., ore**), **secondary sources** (**unconventional resources**) are the focus
- Includes: Cd, Te, In, Ga, Se, and Ge
- Recover Te from copper anode slimes, a byproduct of smelting copper (Rio Tinto, 2022)
- Derive Ga as a byproduct of processing lead-zinc and bauxite ore, along with extraction from zinc (sphalerite) processing residues (USGS, 2017)



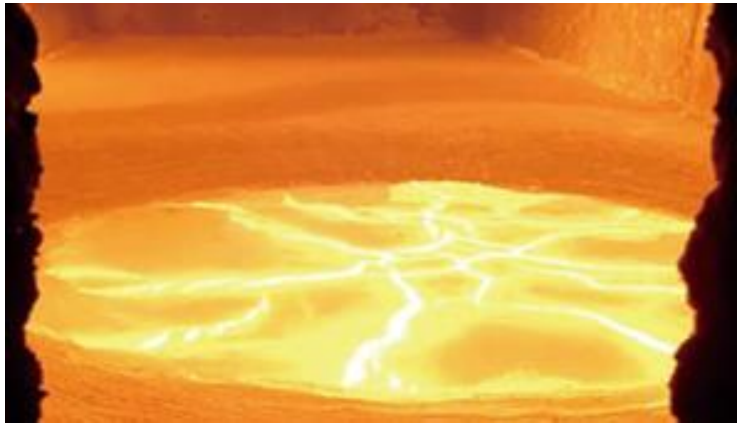


From: National Minerals Information Center, 2017

Occurrence of CM/REE in Mine & Mill Wastes

Porphyry Copper

- Te & Se recovered from smelting
- REE (including Nd & Pr) shown to be present in acidic waters



Copper smelting; photo from Pan Pacific Copper, 2023

Aluminum

Ga recovery from bauxite milling

Coal

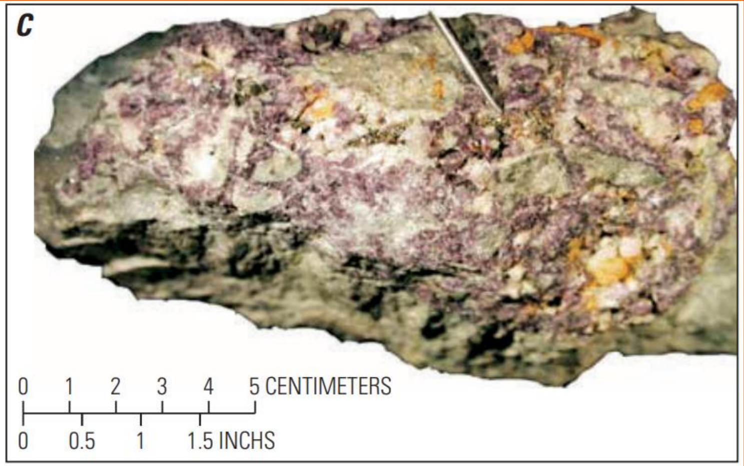
REE present at 100s of ppm; recover from coal ash

Phosphates

- Many REE occur as phosphates
- Milling residues (e.g., phosphogypsum) may have concentrated REE due to prior processing

Gold

- Li, Cu, Zn, Ga, In, & REE may be present, depending on geology
- Alkaline igneous gold deposits shown to have Te & In



Quartz-fluorite-carbonate matrix with accessory pyrite and gold tellurides; photo from USGS, 2010

Iron

Polymetallic iron–niobium–REE deposit, eg. Bayan Obo Inner-Mongolia Mine, China. Contains up to 6% rare earth oxides and 35% Fe

Moran-Palacios, 2019

Bayan Obo Mine; photo from Smith, The Guardian, 2015

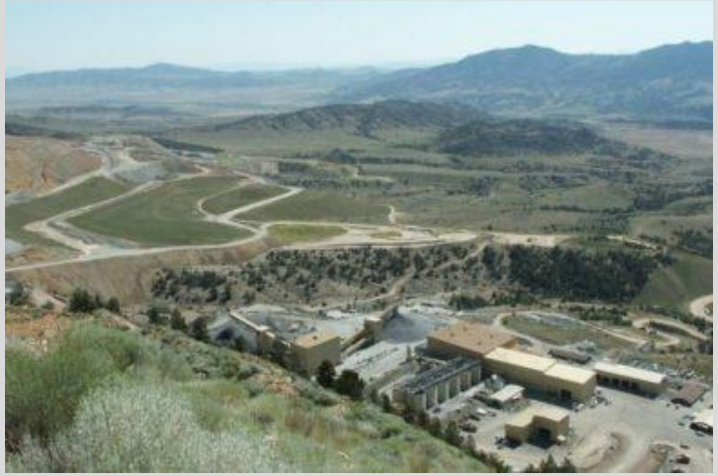
Examples of CM/REE Recovery – Unconventional Sources

Lithium - Boron, CA

- Battery grade lithium produced from waste rock (from 90 years of operations) at the Boron mine site
- Initial pilot 10 tons per year, full scale will be 5,000 tons year (enough for 70,000 EV batteries)

Valorizing Mine Wastes

- Directed at technologies to recover Cu, Ni, Co, Li, Zn, Mn, and REEs from wastes
- “Sustainable mine water remediation”
- Proof of concept to advanced technologies

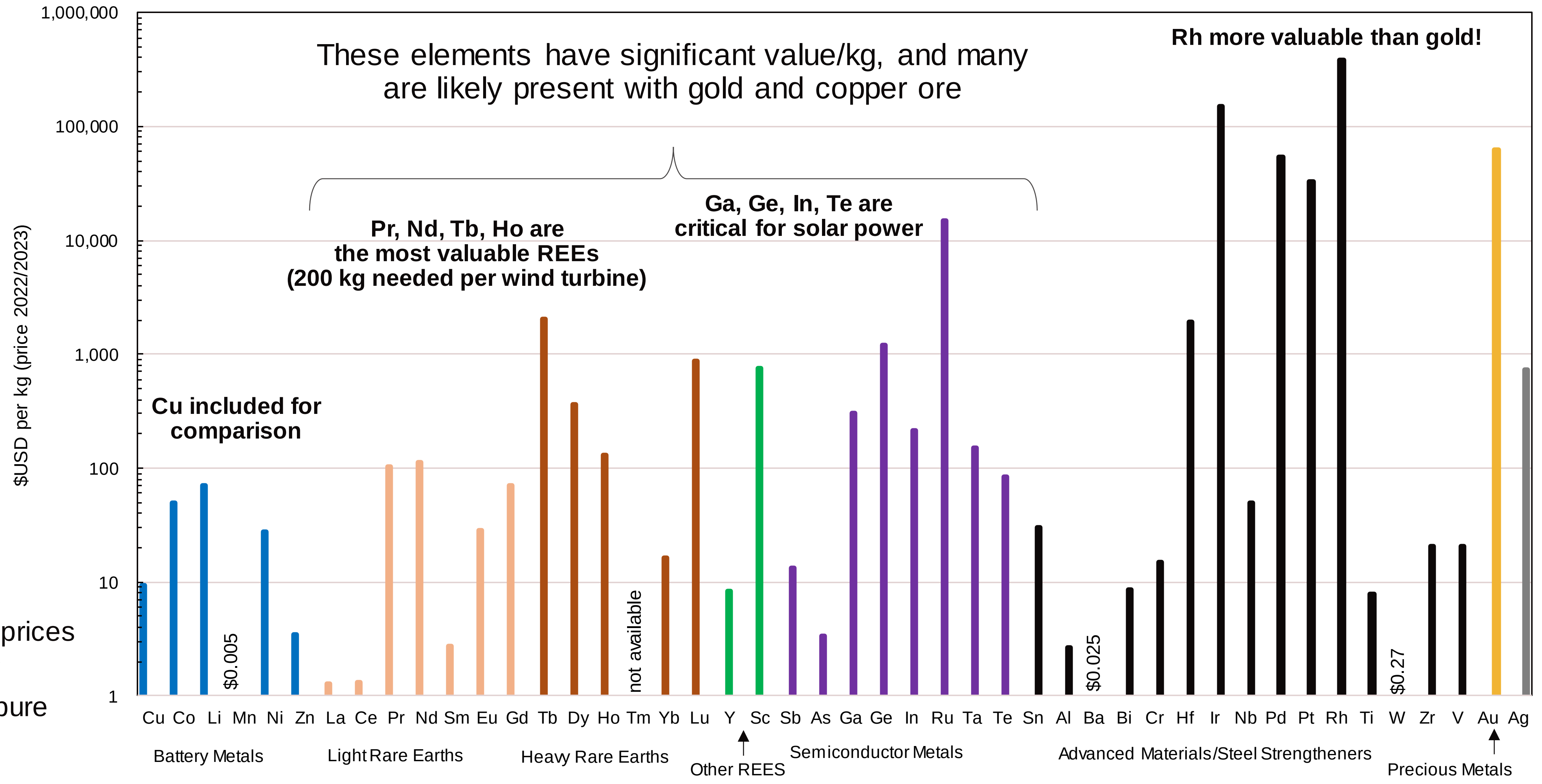


Rare Earth Refinery

- As part of the Bipartisan Infrastructure Law, US Department of Energy is funding a $160 million program to site a REE refinery in the US, specifically for mine wastes
- Facility will produce 1 – 3 tons/day of REE at >90% purity
- “Hub and spoke” concept for supply

“Concept: “REE Concentrates” generated at reclaimed mine for shipment to refinery

CM/REE Pricing



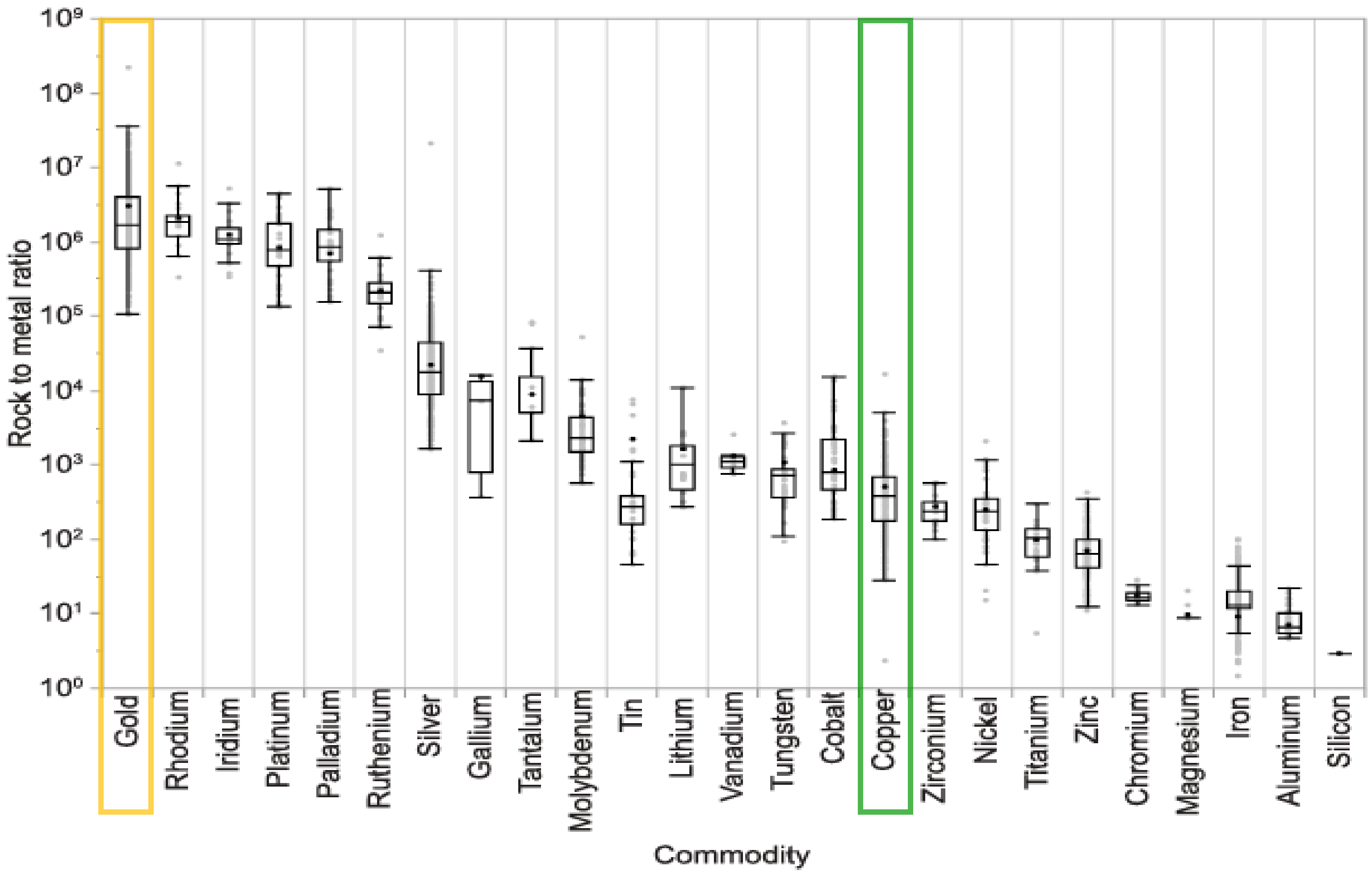
Notes

Snapshot; prices are volatile

Based on pure metals

Rock-to-Metal Ratios for Select Elements

Gold and copper mining generates significant volumes of waste materials (waste rock/tailing)



From: Nassar, 2022 (ES&T)

Benefits of Recovery from Wastes

- Additional revenue stream
- Energy-intensive extraction, milling, crushing, etc. already complete
- Manage site environmental footprint and achieve environmental, social, and governance (ESG) goals
- Benefit operations and minimize future environmental liabilities
  - Reduce hazardous characteristics of wastes through the recovery process (e.g., acidity, metals content)
  - Support mine closure by reducing waste volumes

High-level mining product recovery process

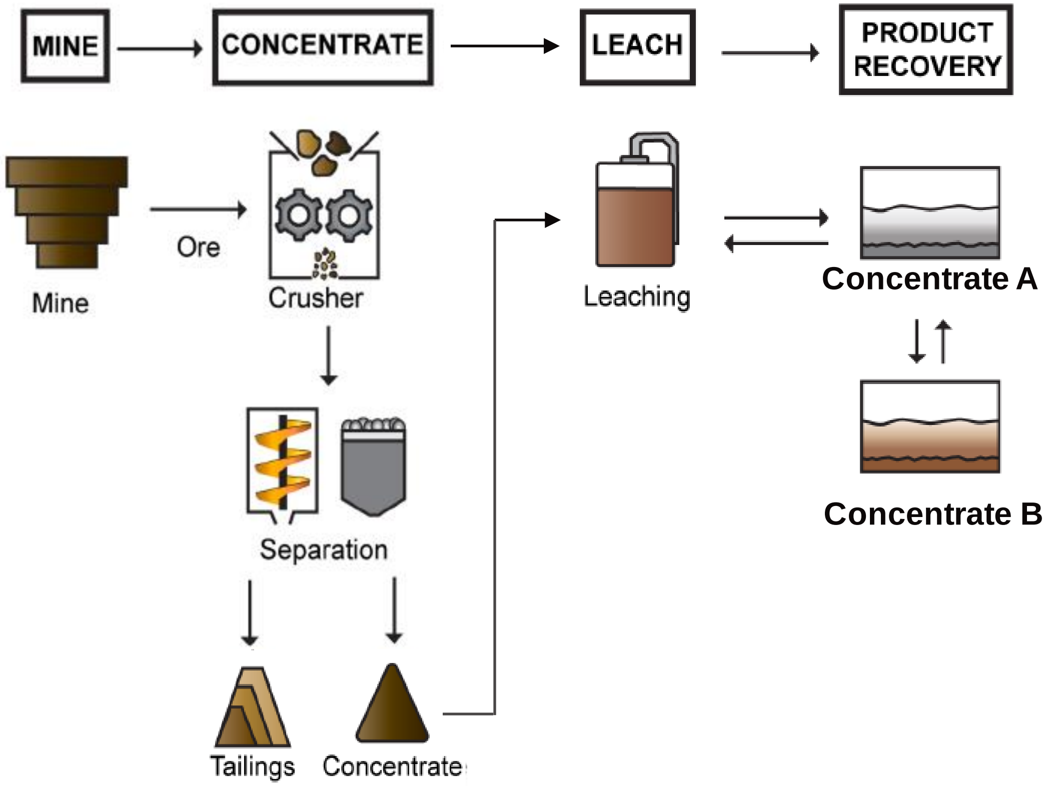


Figure adapted from Whitworth et al., 2022

Critical Mineral Evaluation – Typical Workflow

1 – Preliminary Resource Assessment – Review existing site data & conditions, historical records, and local/regional geology for:

- Site-specific **occurrence of CM/REE**
- **Engineering considerations** (e.g., existing site equipment, recovery efficiency, screen technologies)
- Calculate **potential value** associated with known (or inferred) CM/REE in various waste streams (spent ore, waters, wastewaters) – defining focus of future efforts

2 – Investigate & Refine – Sampling, refine engineering process flow, Go/No-Go on recovery

3 – Regulatory approval process – mine wastes, industrial wastes – requirements vary

4 – Implement – pilot test to full-scale

Mine Geology & Geochemistry

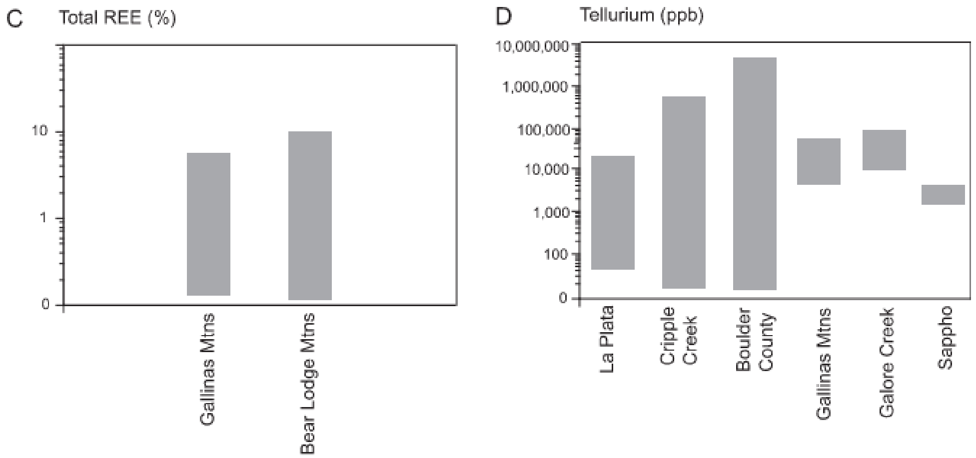
Potential target CM/REE based on:

- Literature on occurrence in the given geology
- Site data if available

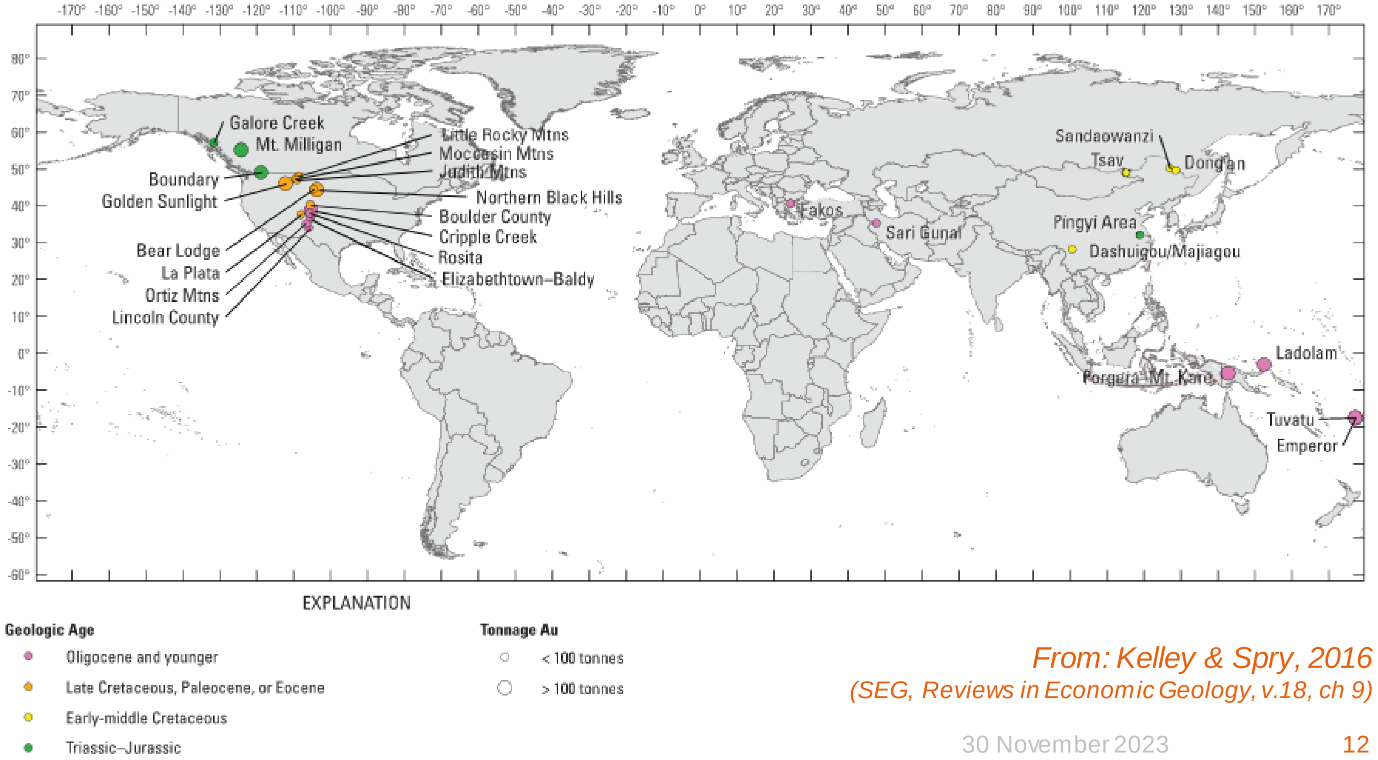
Gold mine with alkaline igneous epithermal geology. Expect:

- Photovoltaic: Te, In, Ga, etc.
- Battery: Zn, Cu, etc.
- REE: Dy, Pr, etc.
- Others: e.g., V

CM/REE in epithermal alkaline gold deposits



Locations of epithermal gold deposits associated with alkaline rocks



From: Kelley & Spry, 2016
(SEG, Reviews in Economic Geology, v.18, ch 9)

Historic Operations & Current Conditions

Past operations inform likely condition of wastes, e.g., gold mining methods:

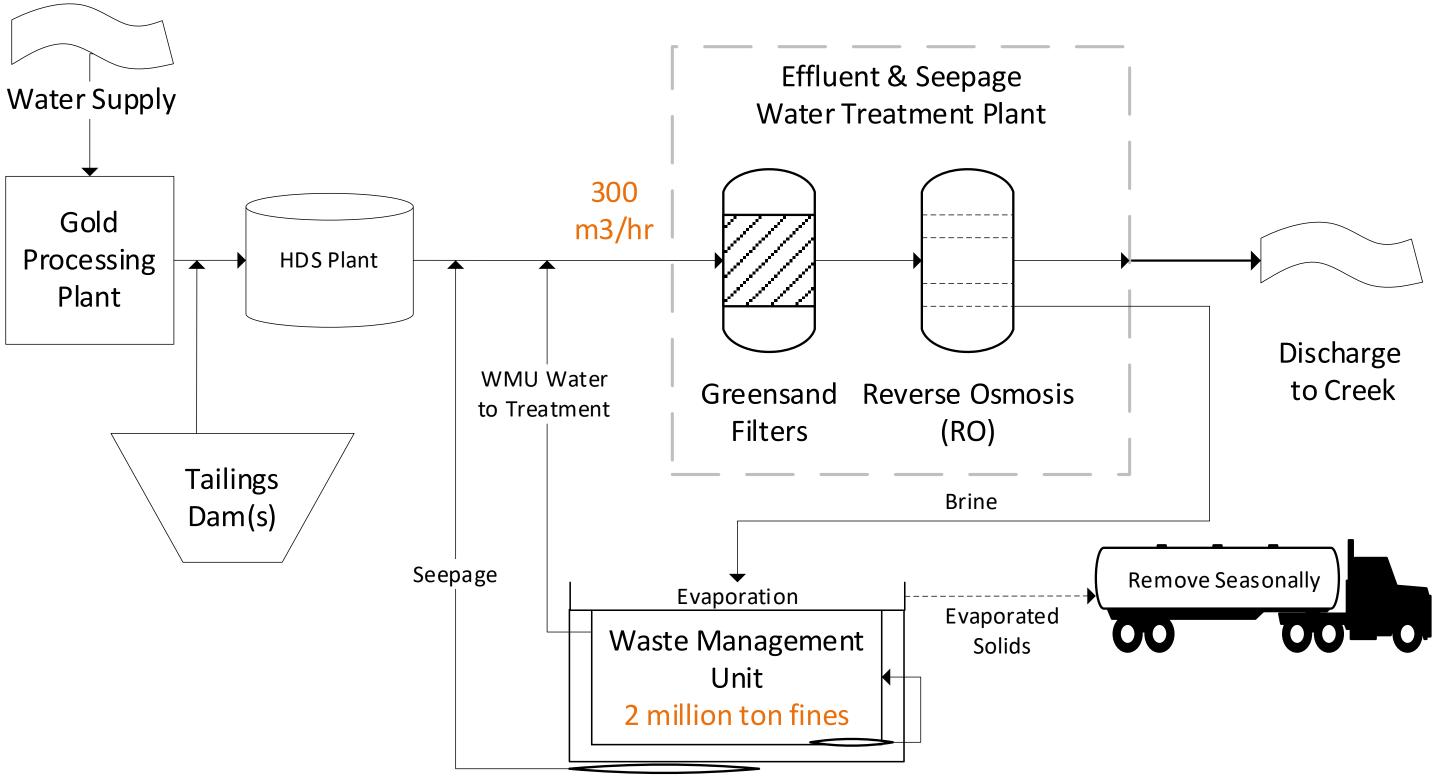
- Open pit, blast, crush ore
- Roast if sulfide minerals
- Cyanide to leach gold
- Activated carbon to recover gold

Current waste conditions:

- Volumes / flowrate of waste rock and tailings / spent ore
- Characteristics & sampling data

Existing treatment / waste management equipment, such as:

- Reverse osmosis (RO)
- High density sludge (HDS) system

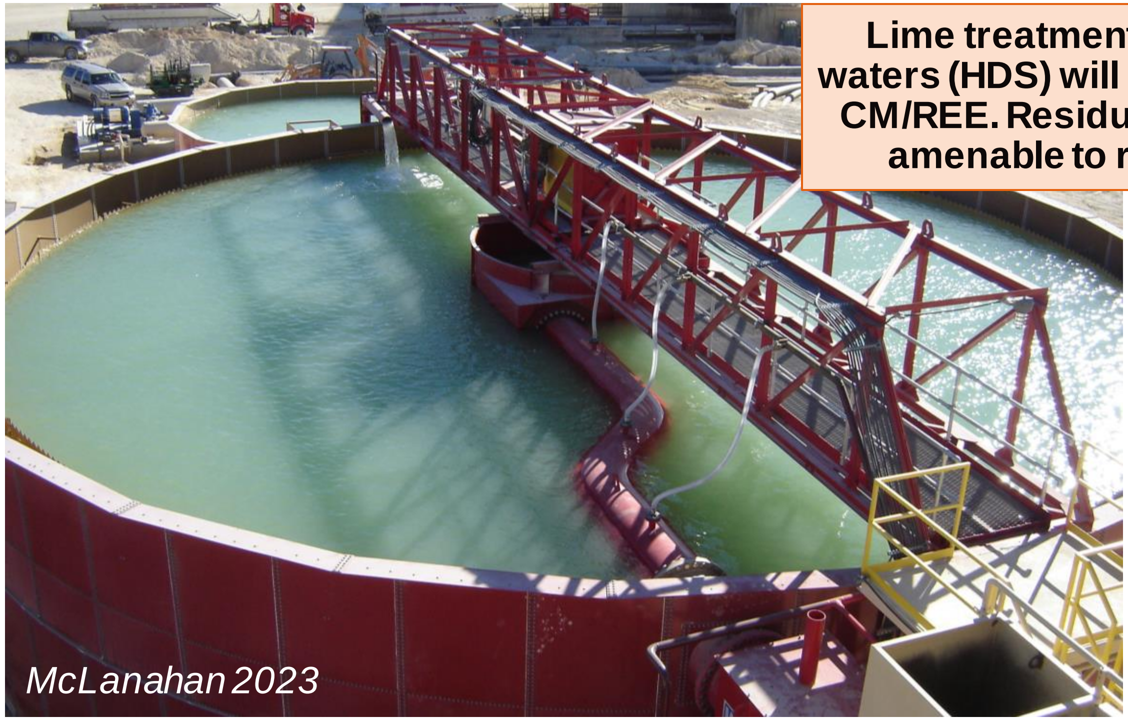


Understand existing site equipment and waste materials (type, volume, concentrations)

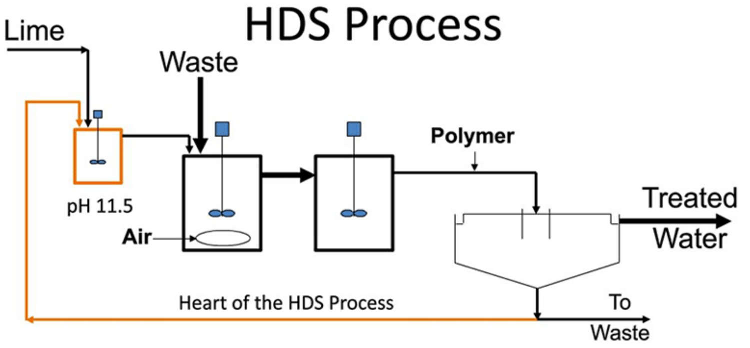
Engineering Strategy

- Relevant technologies to recover CM/REE from waste media
- Use and repurpose of existing equipment and associated wastes, such as:
  - HDS / lime solids
  - RO / brines
- Expected recovery efficiency

Lime treatment of acidic waters (HDS) will concentrate CM/REE. Residuals may be amenable to recovery

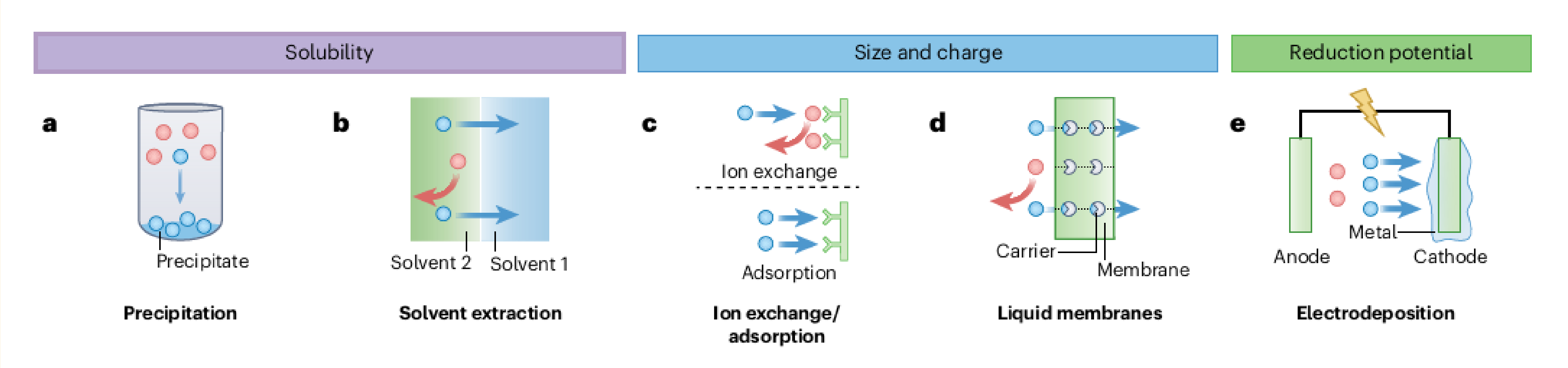


McLanahan 2023



WesTech 2023

Recovery Concepts – Waters/Brine and Spent Ore Leach



From: DuChanois et al., 2022

a. Precipitation based upon solubility (saturation index) and pH
b. Recovery into a solvent that provides physical separation of target CM/REE from aqueous phase
c. Interaction with solid resin through anion or cation exchange
d. Association with a carrier molecule that transport target CM/REE across a membrane
e. Electrochemical reduction and deposition onto a cathode

Recovery – Liquids

Goal: produce 1+ concentrate(s) with CM/REE for further refining

Membrane technologies: direct CM/REE to brine streams, amenable to further recovery

	Monovalent ions	Multivalent ions	Viruses	Bacteria & Algae	Suspended Solids
Microfiltration				X	X
Ultrafiltration			X	X	X
Nanofiltration		X	X	X	X
Reverse Osmosis	X	X	X	X	X

Element		Solubility		Size and Charge		Reduction / Oxidation Potential	
		Precipitation	Solvent Extraction	IX & Adsorption	Membrane Separation	Chemical Red / Ox	Electro-deposition
Battery Metals							
Copper	Cu	X	X	X	X	X	X
Cobalt	Co	X	X	X	X	X	X
Nickel	Ni	X	X	X	X		X
Zinc	Zn	X	X	X	X		X
PV Metals							
Tellurium	Te		X	X	X	X	X
Gallium	Ga		X	X	X	X	X
Indium	In	X	X	X	X	X	X
Advanced Materials							
Vanadium	V		X	X	X	X	X
Rare Earth Elements							
Praseodymium	Pr	X	X	X	X		
Neodymium	Nd	X	X	X	X		
Dysprosium	Dy	X	X	X	X		

Recovery – Solids

Goal: produce 1+ concentrate(s) with CM/REE for further refining

- Mining, crushing generally not needed
- Particle size separation may be needed to isolate highest value materials
- Concentrate may be leached in a tank; to mobilize CM/REE for recovery from liquid
- Existing water treatment infrastructure may be supplemented to recover CM/REE from leach and water/wastewaters

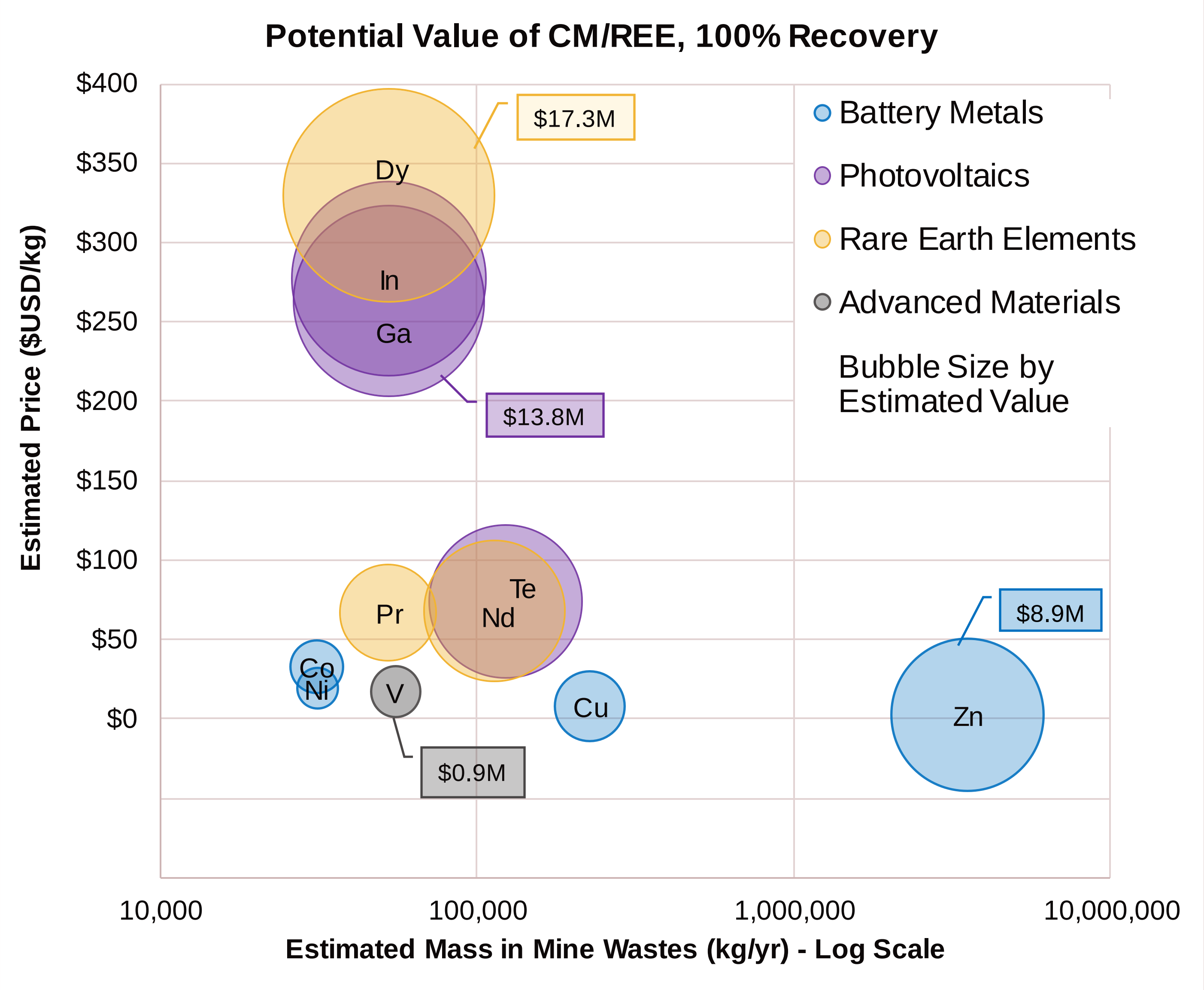
Element		Atmospheric Leaching	Pressure Leaching	Bioleaching	Resin-in-pulp	Phyto-mining	Solvo-metallurgy
Battery Metals							
Copper	Cu	X		X			X
Cobalt	Co	X	X	X	X	X	X
Nickel	Ni	X	X	X	X	X	X
Zinc	Zn	X		X			X
PV Metals							
Tellurium	Te	X	X	X			X
Gallium	Ga	X		X			
Indium	In	X		X			
Advanced Materials							
Vanadium	V	X	X	X			X
Rare Earth Elements							
Praseodymium	Pr	X		X			X
Neodymium	Nd	X		X			X
Dysprosium	Dy	X		X			X

Potential Value

Compare projected value of potential CM/REE to define focus of investigative efforts

Evaluate with respect to:

- Extractability from waste stream
- Buyers in the CM/REE market + proximity to refinery
- Benefits to site (environmental liability, operations, etc.)



Critical Mineral Evaluation – Next Steps

1 – Preliminary Resource Assessment – Review existing site data & conditions, historical records, and local/regional geology for:

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- **Engineering considerations** (e.g., existing site equipment, recovery efficiency, screen technologies)
- Calculate **potential value** associated with known (or inferred) CM/REE in various waste streams (spent ore, waters, wastewaters) – defining focus of future efforts

2 – Investigate & Refine

- Prepare **sampling and analysis plan to fill data gaps** with respect to concentration data for the material; compare site results to published benchmarks
- **Refine engineering evaluation**: target specific CM/REE, narrow to optimal technologies for extraction & recovery from relevant media (eg. mine wastewater, waste rock), draft process flow diagrams
- **Go/No-Go** – including evaluation of costs, potential buyers of CM/REE, and recovery benefits for closure / to minimize potential liabilities

3 – Regulatory approval process – mine wastes, industrial wastes – requirements vary

4 – Implement – pilot/field testing to full-scale implementation

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