Strategic Metals in Batteries: Clean Tech Possibilities
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Outline

• Introduction to metals and where they come from
• Battery technologies – old and new
• Batteries ingredients supply – extraction and economics
  • Lithium, Cobalt, Nickel, Manganese
  • Complexities of geology, geography, trade
  • Sustainability factors
• Circular economy opportunities – reuse and recycling
• Conclusions
 Metals and where they come from

Profitably reducing impacts from mining
Where do metals come from?

• All metals in use, at one point, were mined

• Once metals extracted and produced there is potential for recycling
Metals mining 101

• Geological concentrations of metals, usually in mineral form:
  • Copper in chalcopyrite, a copper iron sulfide – CuFeS$_2$
  • Cobalt in cobaltite, a cobalt arsenic sulfide – CoAsS
  • Nickel in Ni bearing limonite (iron rich clay), etc.

• Mining method – depends on geology, geometry and economic parameters

• Processing to recover and refine metals – depends on geology, customer requirements, cost of energy and consumables, location
Resources and reserves

- Leading codes in the world:
  - JORC - Australia
  - CIM – Canada (NI 43-101)

- Specific definitions of resources and reserves, require competent or qualified persons to assess

- Resources and reserves determined by geological attributes and economics (metal prices, costs) => economic cut-off grade

- Reserves needed to get funded to build a mine
Mineral resource

• “a concentration or occurrence of natural, solid, inorganic, or fossilized organic material in or on the Earth’s crust in such form and quantity and of such a grade or quality that it has reasonable prospects for economic extraction. The location, quantity, grade, geological characteristics, and continuity of a Mineral Resource are known, estimated or interpreted from specific geological evidence and knowledge”

• CIM, 2003
Mineral reserve definition

• “the economically mineable part of a Measured or Indicated Mineral Resource demonstrated by at least a Preliminary Feasibility Study. This study must include adequate information on mining, processing, metallurgical, economic, and other relevant factors that demonstrate, at the time of reporting, that economic extraction can be justified. A Mineral Reserve includes diluting materials and allowances for losses that may occur when the material is mined.”

• CIM, 2003
Metal friends

Profitably reducing impacts from mining
Companion metals

Source: Nassar, 2015

Fig. 1. The periodic table of companionality on a global basis for 2008. Metals that are mainly produced as hosts appear in blue, and those that are mainly produced as companions are in red. Details regarding data sources and assumptions are presented in the Supplementary Materials.
# Base metals companion metals

<table>
<thead>
<tr>
<th>Base metal</th>
<th>Lead and Zinc</th>
<th>Copper</th>
<th>Nickel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Major economic companions</strong></td>
<td>Gold</td>
<td></td>
<td>Platinum group</td>
</tr>
<tr>
<td>(revenue paid to mine)</td>
<td>Silver</td>
<td></td>
<td>Cobalt</td>
</tr>
<tr>
<td></td>
<td>Molybdenum</td>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td></td>
<td>Uranium</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Minor economic companions</strong></td>
<td>Copper</td>
<td>Zinc</td>
<td>Silver</td>
</tr>
<tr>
<td>(generally not paid to mine,</td>
<td>Gold</td>
<td>Lead</td>
<td>Gold</td>
</tr>
<tr>
<td>revenue to refinery)</td>
<td>Germanium</td>
<td>Selenium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indium</td>
<td>Tellurium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bismuth</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Antimony</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cadmium</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Deleterious (mine penalized)</strong></td>
<td></td>
<td>Arsenic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mercury</td>
<td></td>
</tr>
</tbody>
</table>

Categories, revenues or penalties can vary by mine and location.
Companion metals

Cobalt

Silver

Copper

Molybdenum

Source: Nassar, 2015
Batteries – old and new technologies
Batteries

• Store charge
• Components
  • Anode
  • Cathode
  • Electrolyte
  • Casing
• Rechargeable or non-rechargeable
• Variety of chemistries
Rechargeable batteries types

• Pb acid – mature technology, still dominant battery for ICE vehicles, stagnant market
• Ni-Cd – consumer electronics, train and rail cars, not suitable for automotive applications, shrinking market
• NiMh (nickel metal hydride) – early generation HEV (e.g. Toyota Prius) but inferior energy density vs. Li-ion, stagnant
• Li-ion – emerging as the preferred type, range of chemistries, rapid growth

Profitably reducing impacts from mining
Pb supply – dominated by recycling

80% of Pb production used in Pb acid batteries, which have ~95% recycle rate

Source: ILZSG, Market Outlook, Apr 2016
Lithium rechargeable batteries

• Li-ion – current standard - Graphite anode + liquid electrolyte + metal oxide cathode

• Various cathode materials
  • LCO - LiCoO₂
  • NMC - Li(NiₓMn₂Co₁₋ₓ₋₂)O₂ – typically 1/3, 1/3, 1/3 or 0.4, 0.4, 0.2
  • LFP – LiFePO₄
  • NCA – LiNi₀.₈Co₀.₁₅Al₀.₀₅O₂
  • LMO – LiMn₂O₄

• Emerging technologies
  • Li-S – Li metal anode + liquid electrolyte + S cathode
  • Lithium titanate
Auto battery growth

Source: Albemarle, 2015

Profitably reducing impacts from mining

18
How do Ni and Co get into battery?

1. Nickel dissolved in sulphuric acid
2. Solvent extraction
3. Mixing, calcination and heat treatment

Source: BHP Billiton, 2016
Supply and demand: Li battery ingredients
Lithium

• Two sources
  • Li rich brines – mainly from altiplano region in South America
  • Li bearing rocks (spodumene) – USA, Australia, Canada

• Brines have lower costs and environmental impact and projects can be built faster, provided they can meet product quality

• Brines can produce potash (KCl) co-product

• New projects and expansions in both brines and rock
Lithium deposits

• Resources at 2012

Source: Camille Grosjeana, Pamela Herrera Miranda, Marion Perrina, Philippe Poggi, Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry, 2012
Lithium mines

- Greenbushes, Western Australia
- Talison, now controlled by Chinese
- Largest Li mine in the world
Lithium brine production

- Salars of Northern Chile and Argentina
- SQM, Albermarle, FCM, Orocobre
- Large evaporation ponds, recover Li salts with potential potash (KCl) by-product
# Lithium products - forms and uses

<table>
<thead>
<tr>
<th><strong>Key Products</strong></th>
<th><strong>Key Applications</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium Carbonate</td>
<td>Electronics, Li-Ion Batteries, Glass Ceramics, Cement, Aluminum</td>
</tr>
<tr>
<td>Lithium Hydroxide</td>
<td>Li-Ion Batteries, Grease, CO₂ Absorption, Mining</td>
</tr>
<tr>
<td>Lithium Metal</td>
<td>Li Primary Batteries, Pharmaceuticals, Al-Alloys</td>
</tr>
<tr>
<td>Organometallics</td>
<td>Elastomers, Pharmaceuticals, Agrochemicals, Electronic Materials</td>
</tr>
<tr>
<td>Special Salts</td>
<td>Scintillation, Industrial Catalysis, Airbag Ignition</td>
</tr>
</tbody>
</table>

Source: Albemarle, 2015
2015 World Lithium Demand by Product Type (t LCE)

- Battery grade Li-carbonate: 34,430
- Technical grade Li-carbonate: 55,299
- Mineral concentrate: 17,126
- Technical grade Li-hydroxide: 10,765
- Battery grade Li-hydroxide: 7,627
- Butylithium: 7,188
- Bromide: 14,912
- Battery grade Li metal: 32,445
- Other: 2,883


- Different product types sell for different prices
- Most sales by contract, limited price transparency
- Makes harder to evaluate new projects
2015 World Lithium Demand by First Use (t LCE)

- Rechargeable battery: 66,260 t LCE
- Ceramics: 23,782 t LCE
- Glass ceramics: 19,518 t LCE
- Greases: 14,817 t LCE
- Glass: 12,705 t LCE
- Metallurgical powders: 9,156 t LCE
- Polymer: 7,918 t LCE
- Air treatment: 7,188 t LCE
- Primary battery: 16,692 t LCE
- Aluminium: 2,926 t LCE
- Other: 1,714 t LCE

Lithium prices

- Different grades sell for different prices – lowest to highest
  - Spodumene concentrate
  - Technical lithium carbonate
  - Battery grade lithium carbonate
  - Technical lithium hydroxide
  - Battery grade lithium hydroxide
  - Battery grade lithium metal

- Meeting quality spec is critical for realizing high price

- Prices reflect conversion costs – largely driven by reagents
Lithium prices

- Recent battery grade Li carbonate around $15,000/t
- About $2,500/t premium for producing LiOH.H₂O
Lithium greenfield/expansion projects

• Talison (Tianqi) - Salares 7, brine, Northern Chile
• Tianqi – battery grade LiOH plant in Kwinana, WA, converting spodumene concentrate from Greenbushes mine
• Galaxy Mount Cattlin, WA, spodumene concentrate
• Lithium Americas + SQM - Argentina
• Many juniors, some projects will fail
• Possibility that supply will come on too fast for demand increases, causing drop in prices
Cobalt and nickel

Profitably reducing impacts from mining
Cobalt

• Rare metal produced almost exclusively as a by-product of processing copper and nickel ores:
  • Stratiform copper deposits in African Copper Belt – mostly in the DRC side
  • Nickel-cobalt laterite deposits in New Caledonia, Australia, Philippines, Cuba
  • Nickel-cobalt-PGM sulfide deposits in Canada and Russia

• By-product production from Cu mines dominated by oxide deposits in DRC

• Complex processing from Ni deposits due to affinity of Ni and Co
Profitably reducing impacts from mining

- Ambiguity between mined and refined production
- World production in 2015 approx. 98,000 t

Source: Cobalt Development Institute, 2016
Cobalt prices back on the rise

- Co prices doubled in last year

Profitably reducing impacts from mining
Cobalt prices back on the rise

• But not near the levels of 2008 yet

Source: Cobalt Development Institute, 2016
In 2015, Tenke Fungurume produced approximately 204,000 tonnes of cathode copper and 16,000 tonnes of cobalt in cobalt hydroxide (100% basis). Forecast production for 2016 is as tabulated below.

<table>
<thead>
<tr>
<th>Tenke Fungurume (100%)</th>
<th>Unit</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper Production</td>
<td>'000 Tonnes</td>
<td>224</td>
</tr>
<tr>
<td>Cobalt Production</td>
<td>'000 Tonnes</td>
<td>16</td>
</tr>
</tbody>
</table>

The current copper/cobalt Mineral Reserves at Tenke Fungurume are able to support a mine life in excess of 25 years.

Source: Lundin Mining 2015 AIF
Tenke location, DRC

- One of several large Cu-Co mines on DRC side of the African Copper Belt
Major mines in DRC changing hands

Freeport to sell prized Tenke copper mine to China Moly for $2.65 billion

• China and Glencore moving to take control of DRC Co production

Glencore Buys Out Billionaire With $1 Billion Congo Mining Deal

Franz Wild, Jesse Risborough and Thomas Wilson
February 13, 2017 at 6:26:38 AM PST  Updated on February 13, 2017 at 4:00:01 PM PST

- Glencore to pay Gertler’s Fleurette group $534 million in cash
- Cobalt prices are soaring on demand for rechargeable batteries
DRC – supply chain risk, ethics

- Coltan (columbian tantalate, i.e. Nb, Ta) is key conflict mineral in DRC
- Cobalt mainly comes from other non-conflict regions, but significant artisanal production
- Some environmental, social issues from large mining companies in Katanga
DRC – artisanal Co mining

• Quantities hard to trace - middlemen and opaque trades
• Artisanal concentrates predominantly sold to China
• CRU estimate – artisanal miners in DRC produced concentrates containing 10,500 t Co, approx. 10% of global supply
• Estimated 100,000 artisanal miners in Katanga region of DRC, many are women and children
• NGOs have legitimate concerns re: exploitation, pollution

World Ni supply and demand

• Different ore sources
  • Sulfides – grinding, flotation, smelting, leaching
  • Laterites – hydrometallurgical or pyrometallurgical depending on ore

• Different mine product types
  • Sulfide concentrates to Ni sulfide smelters
  • Saprolite laterites to Ferronickel and Ni pig iron
  • Limonite laterites mostly to pressure leaching refineries

• Dominant use – ingredient in stainless steel – many grades, various substitutes (e.g. Mn, Cr)
Current main production processes for nickel

Note: excludes leaching processes for sulphides (Talvivaara bioleach in Finland) and limonites (in Guangxi and Jiangshi in China)

Source: Macquarie Commodities Research, 2013
Ni use - stainless steel and China

Source: Macquarie Commodities Research, 2013
Ni prices in the doldrums

Nickel Price
4.93 USD/lb
28 Feb '17

Profitably reducing impacts from mining
Asian export bans – Ni uncertainty

• Indonesia:
  • Mining Law No. 4 came into effect 2014
  • Limits export of unrefined Al, Cu, Ni ores and concentrates
  • Standoff with major mining companies, Chinese customers
  • Stimulating some expansion of Indonesian smelting and refining
  • Nationalization strategy?

• Philippines:
  • Mining bans decreed in 2016 based on environmental concerns
  • Affecting Ni, Au the most
  • Appears some companies targeted arbitrarily
Indonesia, Philippines mining bans

Mining ban raises risks in the Philippines

A decision to close, suspend and cancel mining operations has come under fire as yet another of President Rodrigo Duterte’s ill-considered policies.

Shafted

Indonesia and the Philippines hobble the mining industry

Jobs and revenue evaporate as the regulators pile on

Profitably reducing impacts from mining
Indonesian export bans

- 0.9 Mt to 0.2 Mt Ni
- World share 31% to 7%
- Collapse in ore exports impacts Chinese NPI
- Impacts Ni prices

Source: USGS, 2014
• Brazilian owned multinational mining company
• Large miner of Fe ore, Ni
• Co is a key by-product from Ni operations
• 5,799 metric t production in 2016, 28% YOY growth

Profitably reducing impacts from mining
Co and Ni from laterites

• Complex, multibillion $ plants, struggling to pay their way
Co from Ni laterite refining

- QNI, Townsville, QLD, Australia (where I used to live)
- RIP, Dec 2015
- Victim of low Ni prices
Manganese

Profitably reducing impacts from mining
Mn resources – South Africa #1

Note the fine print – bubble size changes significantly with Mn price

Source: E Muller, Manganese Industry Outlook and Opportunities, BHP Billiton, 2014
Mn production and uses

• 90% used in steel alloying

• Most added to furnaces as high grade ore, or crude iron-manganese alloys (ferro-manganese)

• Small fraction is refined to other products:
  • Electrolytic manganese metal (EMM) for stainless steels
  • Electrolytic manganese dioxide (EMD) for batteries

• China dominates all forms of alloying and refining
Challenges and possibilities - metals for batteries
China dominates metal refining

• Since 2000, massive growth in Chinese smelting and refining, now largest for most metals, e.g.:
  • Steel and stainless steel
  • Alumina and aluminum (aluminium)
  • Gold
  • Copper, zinc, lead and nickel
  • Cobalt
  • Electrolytic Mn (EMM) and MnO₂ (EMD)
  • Rare earth elements

• Implications - mining value chain, supply chain transparency
Co, Ni needs - different chemistries

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Cathode stoichiometry</th>
<th>Weight ratio - cathode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Co:Li</td>
</tr>
<tr>
<td>LCO</td>
<td>LiCoO₂</td>
<td>8.5</td>
</tr>
<tr>
<td>NMC – equal ratios</td>
<td>LiNi₀.₃₃Mn₀.₃₃Co₀.₃₃O₂</td>
<td>2.8</td>
</tr>
<tr>
<td>NMC – low Co</td>
<td>LiNi₀.₄Mn₀.₄Co₀.₂O₂</td>
<td>1.7</td>
</tr>
<tr>
<td>NCA</td>
<td>LiNi₀.₈Co₀.₁₅Al₀.₀₅O₂</td>
<td>1.2</td>
</tr>
<tr>
<td>LMO</td>
<td>LiMn₂O₄</td>
<td>0.0</td>
</tr>
<tr>
<td>LFP</td>
<td>LiFePO₄</td>
<td>0.0</td>
</tr>
</tbody>
</table>

• Cathode chemistry has major bearing on Co, Ni requirements
Li-ion battery type predictions

BHP Billiton, major Ni miner, sees NMC and NCA as dominant battery types for vehicles

Source: BHP Billiton, 2016
Substitution potential - ingredients

• Supply chain volatility, quality requirements, competing uses affect decisions about ingredient mixes for batteries

• Substitution abilities
  • Within battery cathode types – e.g. Ni and Mn for Co
  • Within other uses of metals – e.g. Mn (as EMM) substituting Ni in S200 stainless steels

• Substitution depends on relative metals prices and certainty of supply

• Relies on downstream innovation, customer feedback
Hot metals - not always sure bet

• Despite lithium story, advanced projects can fail due to processing and logistics complexities
What to do at end of Pb?

• When Pb acid battery market falls, what happens to Pb?
• Major anthropogenic stocks of Pb, potential environmental issues
• Pb residues management from other metals extraction if Pb market collapses – could fundamentally affect extraction processes and economics (esp. Ag, Zn)
• Are there safe and cost effective applications for Pb batteries?
## Metal supply and demand - what’s in our control?

<table>
<thead>
<tr>
<th>Can’t control</th>
<th>Can control</th>
</tr>
</thead>
</table>
| Geological accumulations:  
  • Where they are  
  • What’s in them - valuables and impurities, form of minerals  
  • Shape of deposits | Where to look for deposits or other stocks of metals  
How to mine and extract metals from deposits  
How we trade metal ores, concentrates and refined products |
| Chemistry fundamentals – will constrain extraction and uses | How and where we use, recycle and dispose |
# Li battery ingredients comparison

<table>
<thead>
<tr>
<th></th>
<th>Li</th>
<th>Co</th>
<th>Ni</th>
<th>Mn</th>
<th>Al</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crustal abundance rank</td>
<td>33</td>
<td>32</td>
<td>24</td>
<td>12</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Current main mine producers</td>
<td>Australia, Chile</td>
<td>DRC</td>
<td>Philippines, Russia, Canada</td>
<td>South Africa, Australia</td>
<td>Australia, China, Brazil</td>
<td>Australia, Brazil, China</td>
</tr>
<tr>
<td>Main refiners</td>
<td>China</td>
<td>China</td>
<td>China</td>
<td>China</td>
<td>China</td>
<td>China</td>
</tr>
<tr>
<td>Supply chain risk</td>
<td>Low</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
Circular economy

Profitably reducing impacts from mining
Umicore – integrated battery recycling

Gas to cleaning station

CO₂
H₂O
Dust (reusable)

Slag to application

Aggregate for concrete
Stone wool
Ceramics

Li&RE recovery

Metals to refining/transformation

Ni, Co
Cu, Fe

New battery materials

LiB-NiMH recycling at Umicore
Jan Tytgat
Conclusions
Conclusions

• Interactions between economics and mineral reserves
• Supply chains for lithium battery metals are complex
  • Limited diversity and transparency of supply, esp. Co
  • Interaction between Ni and Co economics
  • Branding challenges for ethical and sustainability metrics
• Stay alert, validate sources – supply, demand, R & D
• Most roads lead to China, but opportunities for by-passing
• Innovation and substitution are possible, but need a plan