Resourceful Paths

Strategic Metals in Batteries: Clean Tech Possibilities

BERCShop, UC Berkeley

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Outline

Resourceful Paths

- 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

Where do metals come from?

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

- Once metals extracted and produced there is potential for recycling

Resourceful Paths

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

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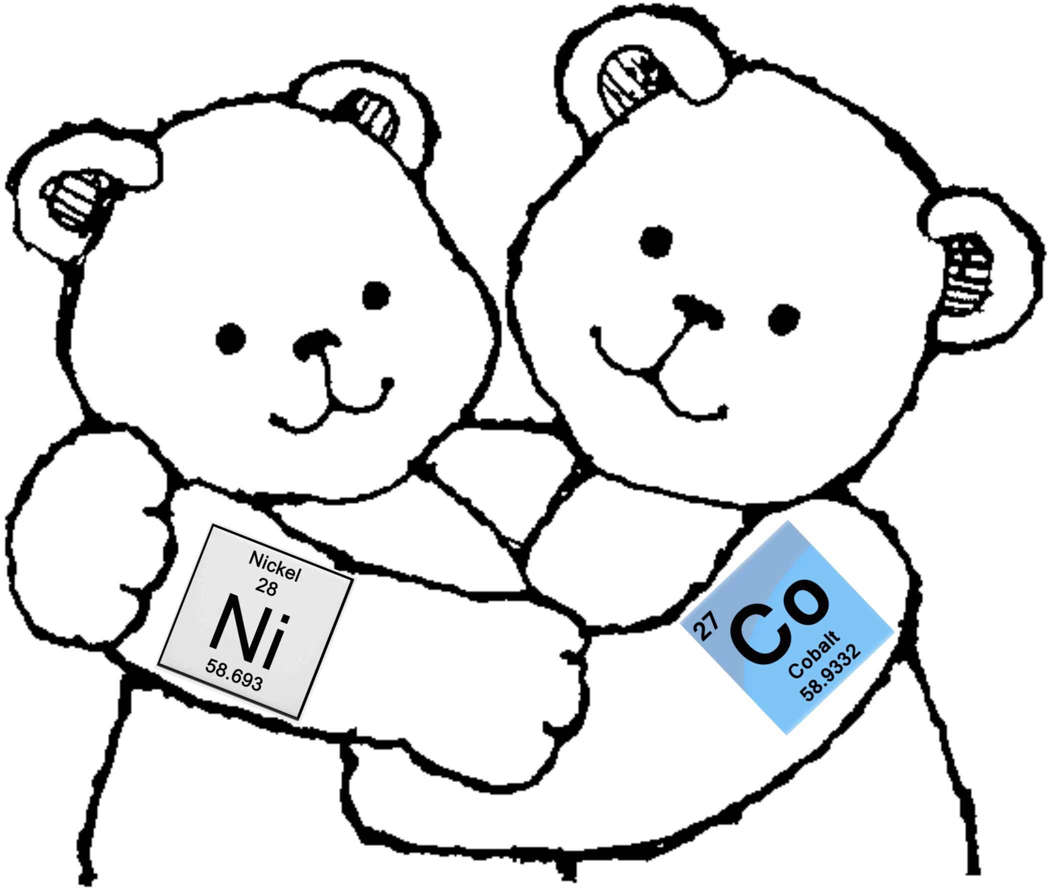
- “a concentration or **occurrence** of natural, solid, inorganic, or fossilized organic material in or on the Earth’s crust **in such form** and **quantity and** of such a grade or **quality that it has reasonable prospects for economic extraction**. The location, quantity, grade, geological characteristics, 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



Companion metals

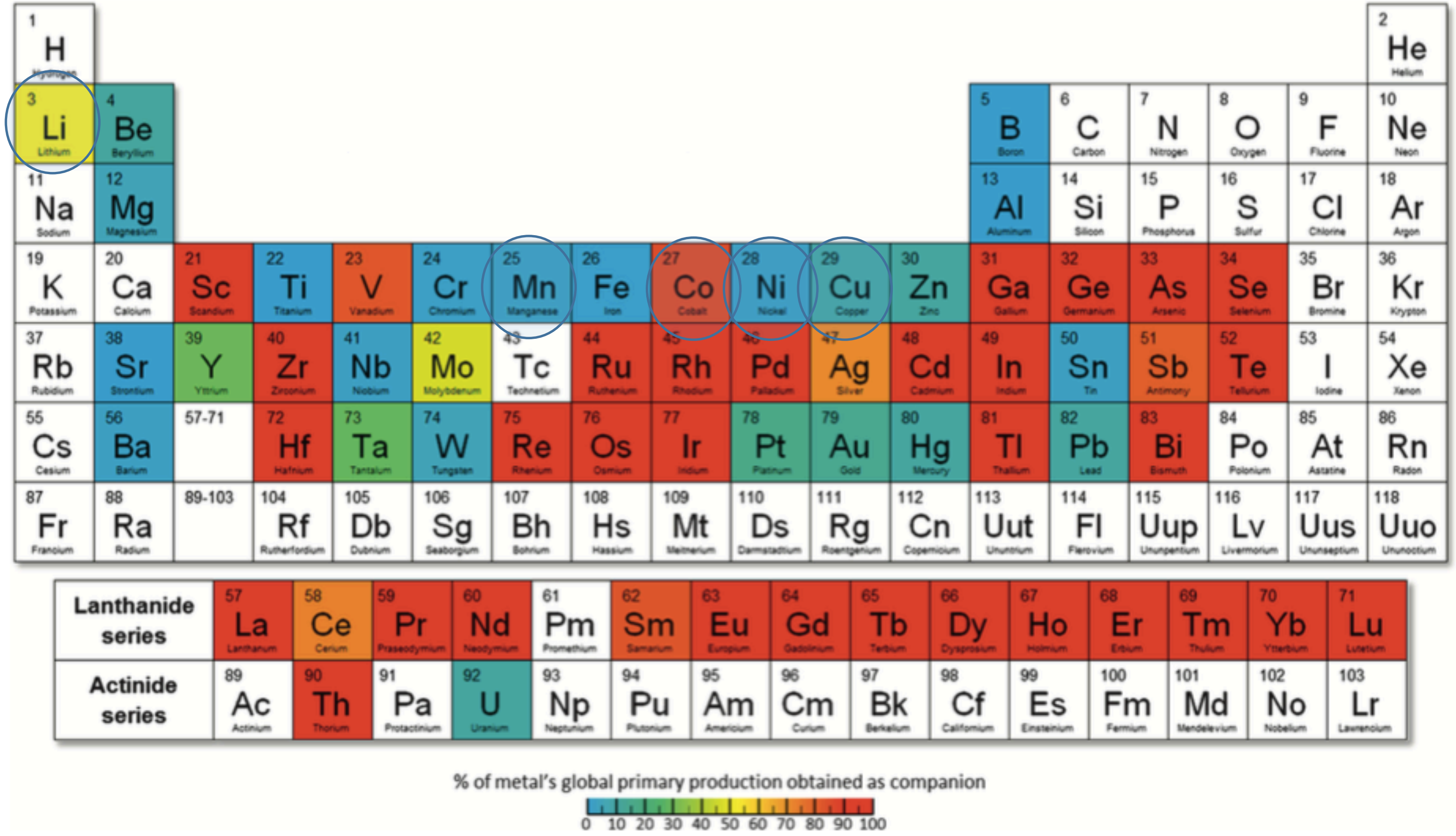


Fig. 1. The periodic table of companionality on a global basis for 2008. Metals that are mainly produced as hosts appear in blue, and those that are mainly produced as companions are in red. Details regarding data sources and assumptions are presented in the Supplementary Materials.

Source: Nassar, 2015

Resourceful Paths

Base metals companion metals

Categories, revenues or penalties can vary by mine and location

<table>
<tr><th>Base metal</th><th>Lead and Zinc</th><th>Copper</th><th>Nickel</th></tr>
<tr><td rowspan="5">Major economic companions (revenue paid to mine)</td><td></td><td>Gold</td><td>Platinum group</td></tr>
<tr><td colspan="2">Silver</td><td></td></tr>
<tr><td rowspan="3"></td><td colspan="2">Cobalt</td></tr>
<tr><td>Molybdenum</td><td>Copper</td></tr>
<tr><td>Uranium</td><td></td></tr>
<tr><td rowspan="7">Minor economic companions (generally not paid to mine, revenue to refinery)</td><td>Copper</td><td>Zinc</td><td>Silver</td></tr>
<tr><td>Gold</td><td>Lead</td><td>Gold</td></tr>
<tr><td>Germanium</td><td>Selenium</td><td rowspan="5"></td></tr>
<tr><td>Indium</td><td>Tellurium</td></tr>
<tr><td>Bismuth</td><td rowspan="3"></td></tr>
<tr><td>Antimony</td></tr>
<tr><td>Cadmium</td></tr>
<tr><td rowspan="2">Deleterious (mine penalized)</td><td colspan="3">Arsenic</td></tr>
<tr><td colspan="2">Mercury</td><td></td></tr>
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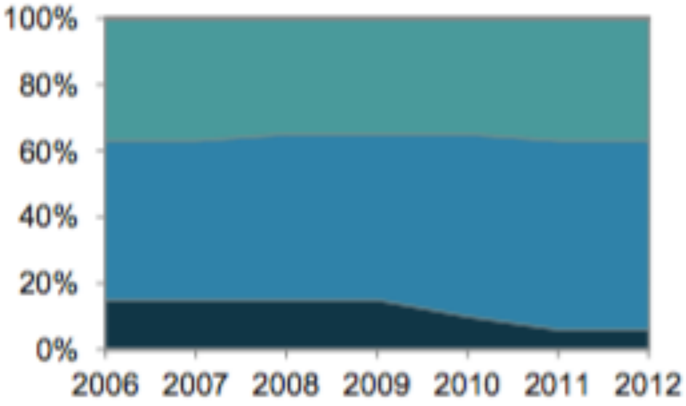
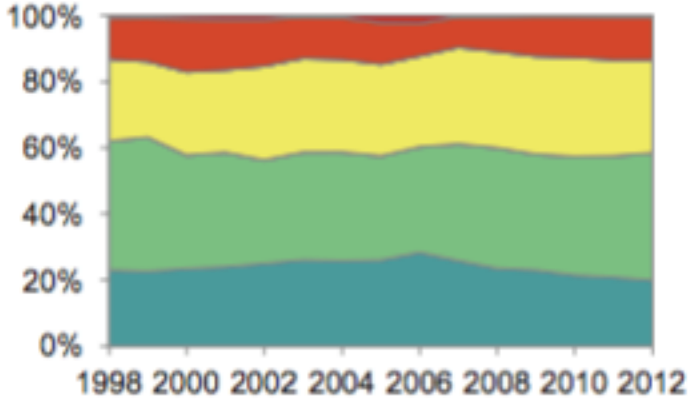
Companion metals

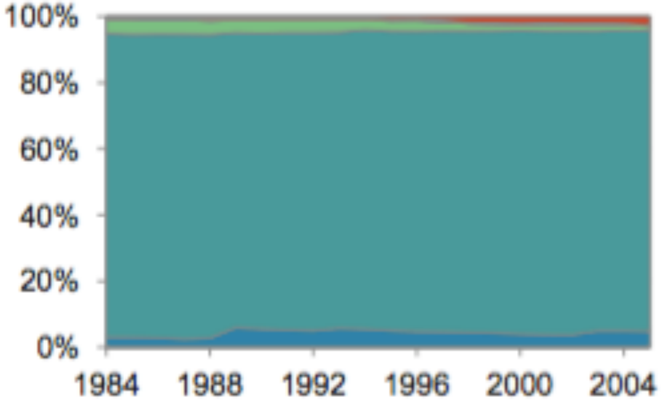
Cobalt



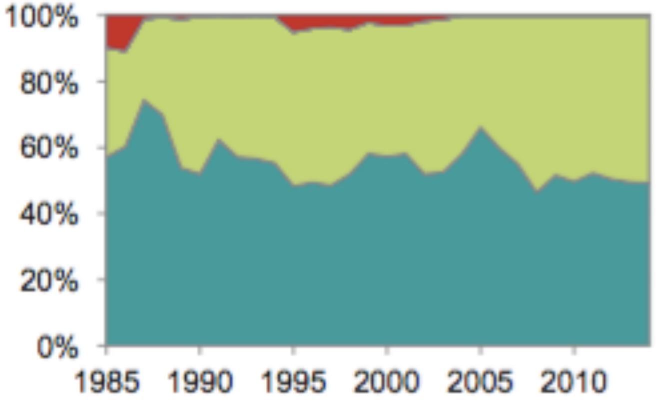
Silver



Copper



Molybdenum



Host metals

- Other
- Au
- Pt
- Ag
- Mo
- Pb/Zn
- Cu
- Ni
- Co

Source: Nassar, 2015

Batteries – old and new technologies

Batteries

Resourceful Paths

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

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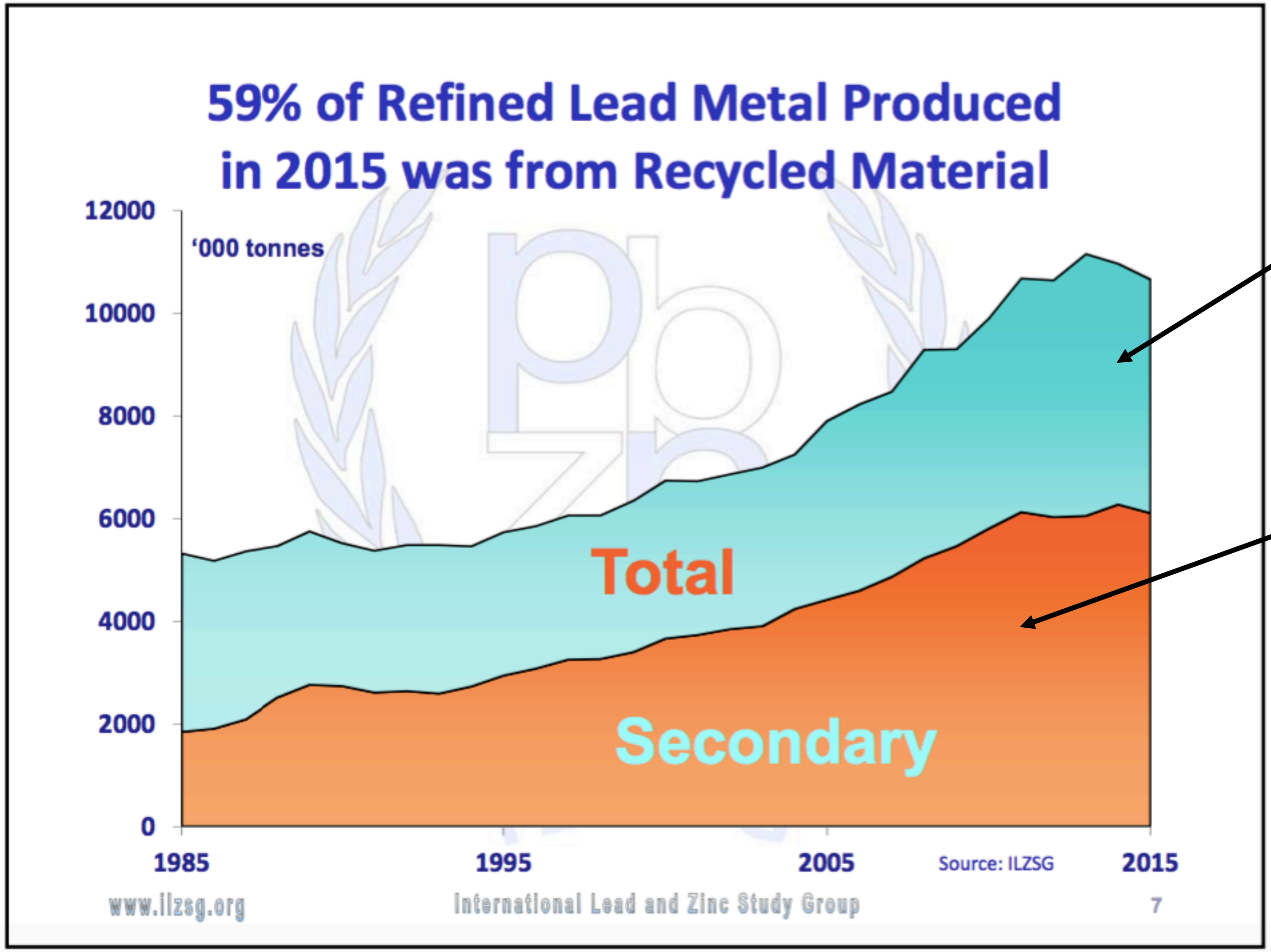
Rechargeable batteries types

- 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

Pb supply – dominated by recycling

Resourceful Paths



Primary – mine production

Recycled

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

Source: ILZSG, Market Outlook, Apr 2016

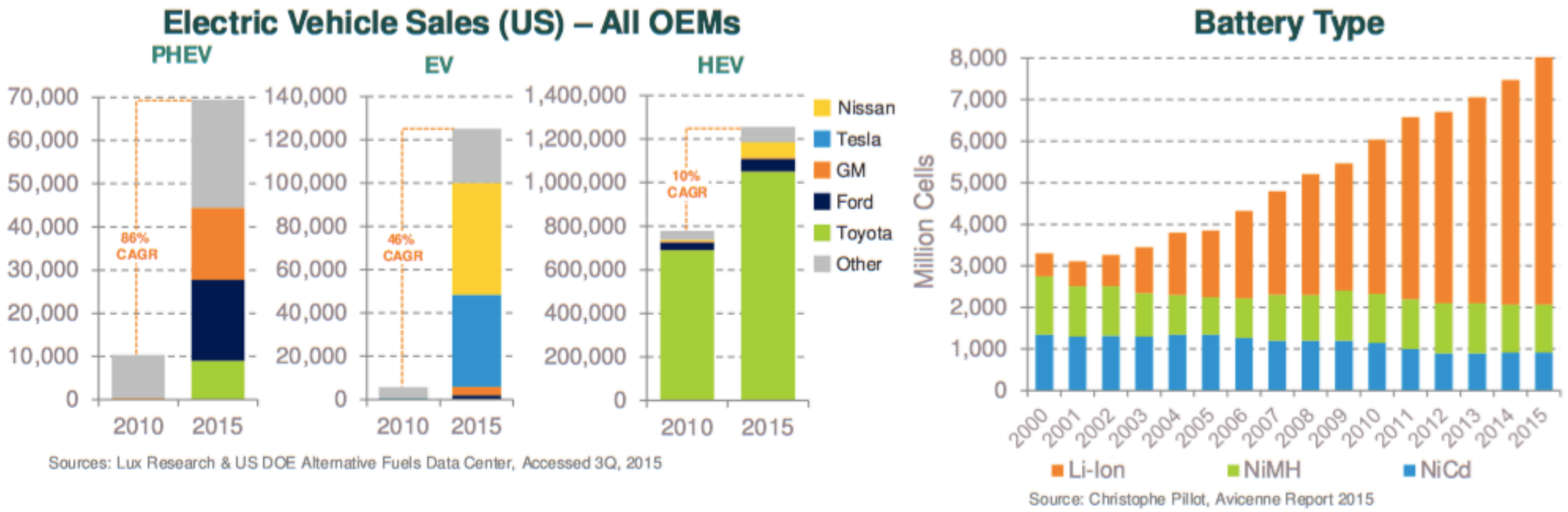
Lithium rechargeable batteries

Resourceful Paths

- Li-ion – current standard - Graphite anode + liquid electrolyte + metal oxide cathode
- Various cathode materials
  - LCO - $LiCoO_2$
  - NMC - $Li(Ni_yMn_zCo_{1-y-z})O_2$ – typically 1/3, 1/3, 1/3 or 0.4, 0.4, 0.2
  - LFP – $LiFePO_4$
  - NCA – $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$
  - LMO – $LiMn_2O_4$
- Emerging technologies
  - Li-S – Li metal anode + liquid electrolyte + S cathode
  - Lithium titanate

Auto battery growth

Resourceful Paths



Source: Albemarle, 2015

How do Ni and Co get into battery?

Nickel dissolved in sulphuric acid

Solvent extraction

Mixing, calcination and heat treatment

Nickel sulphate

Nickel and cobalt sulphate

Battery cathode precursors

Source: BHP Billiton, 2016

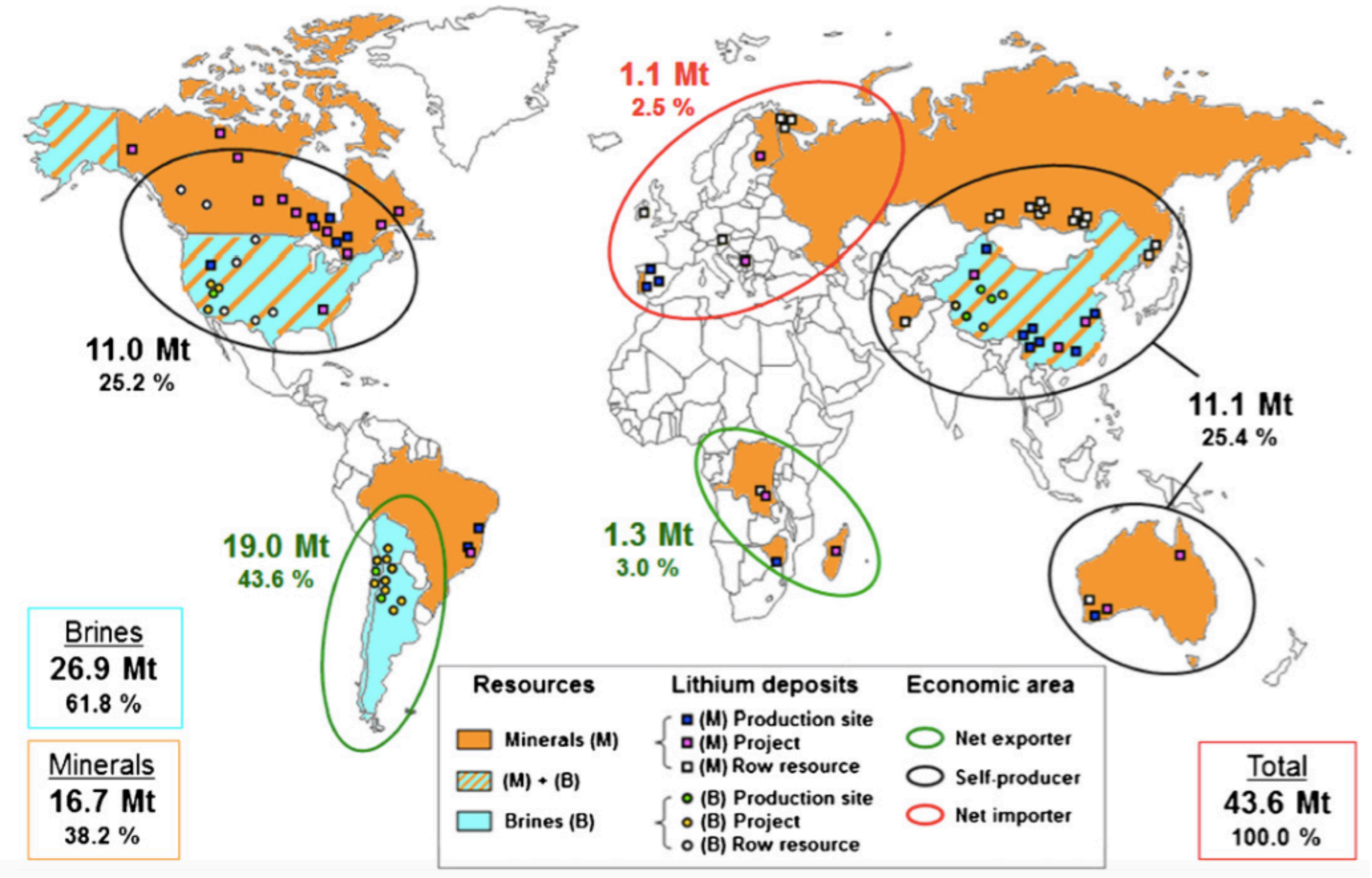
Supply and demand: Li battery ingredients

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

Resourceful Paths

Lithium deposits



- Resources at 2012

Source: Camille Grosjeana, Pamela Herrera Mirandaa, 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

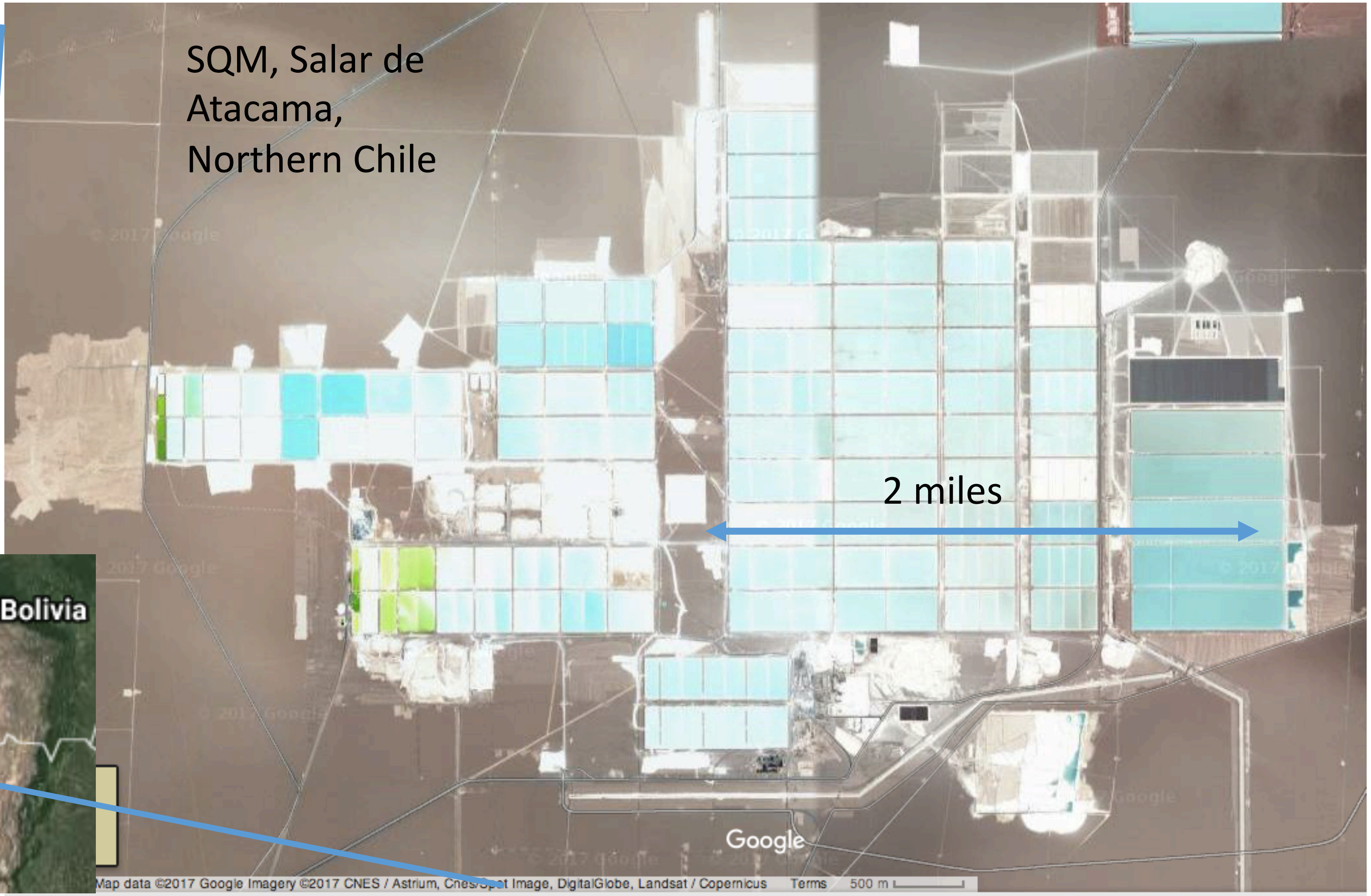
Resourceful Paths

Lithium mines

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

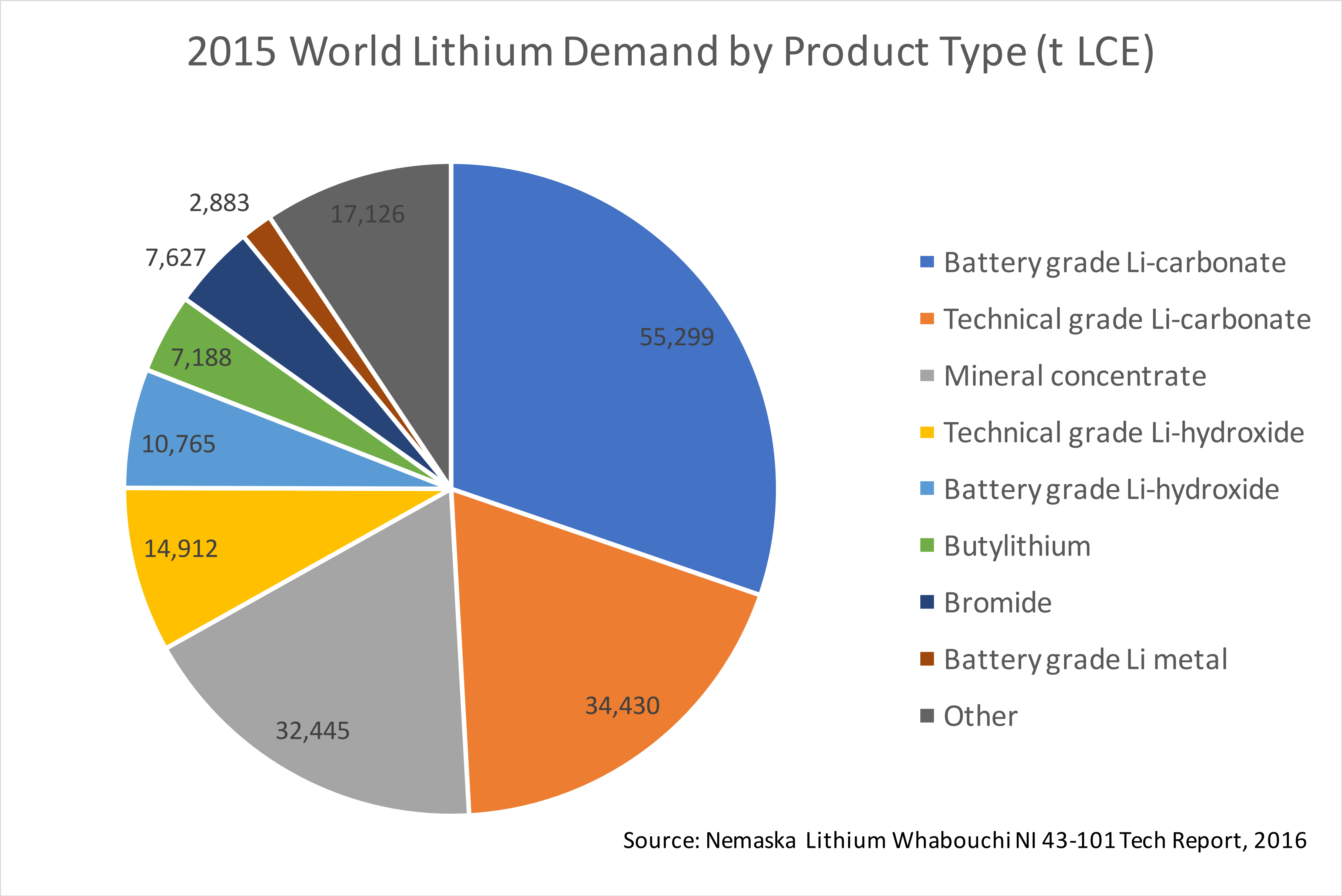
Lithium brine production

- 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

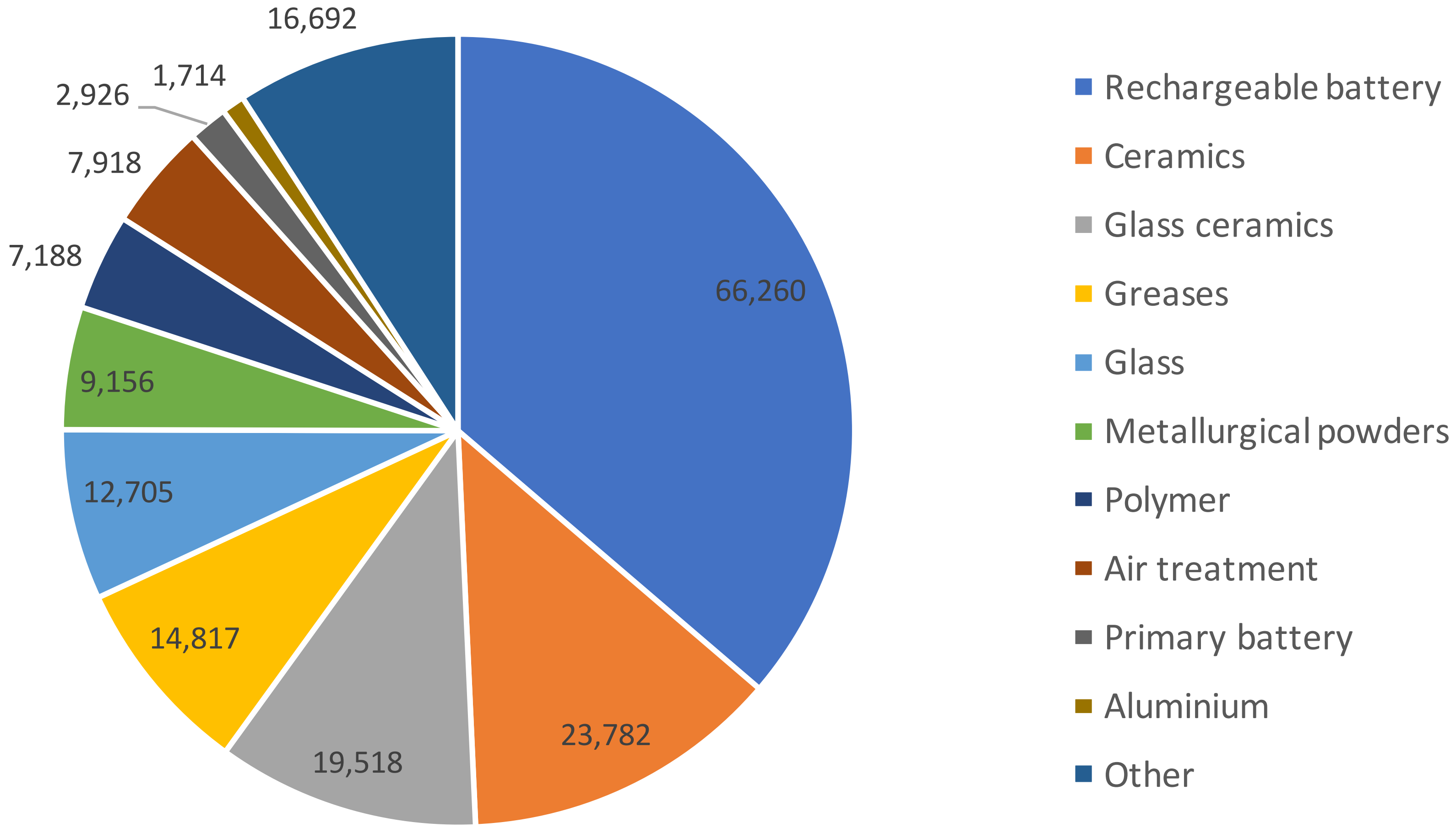
Source: Albemarle, 2015



Resourceful Paths

- 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)



Source: Nemaska Lithium Whabouchi NI 43-101 Tech Report, 2016

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Resourceful Paths

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

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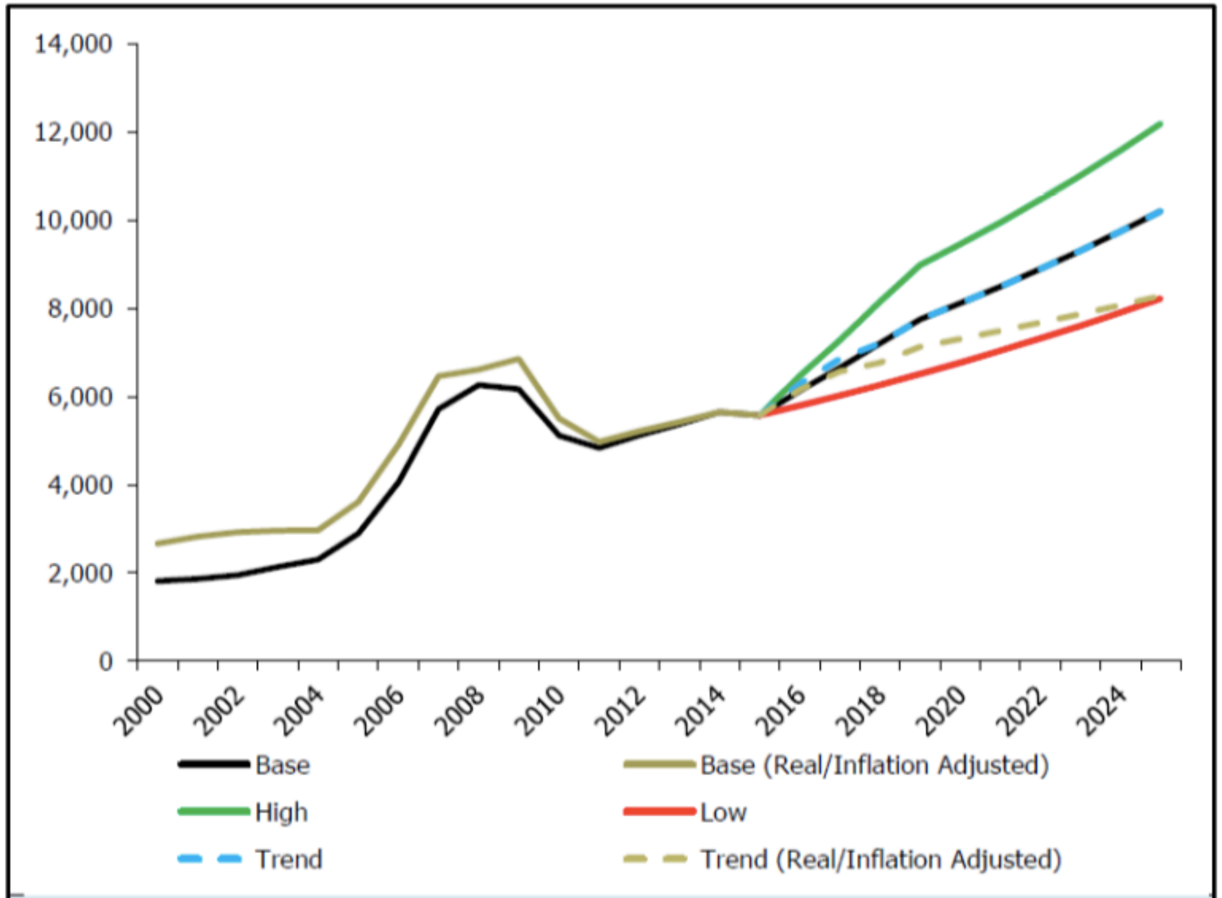
Lithium prices

Figure 19-5 - Price forecast for battery-grade lithium carbonate (US$/t CIF)



Source: Global Trade Atlas
Note: Real prices adjusted to constant US dollars using World GDP deflator data from the International Monetary Fund's World Economic Outlook Database

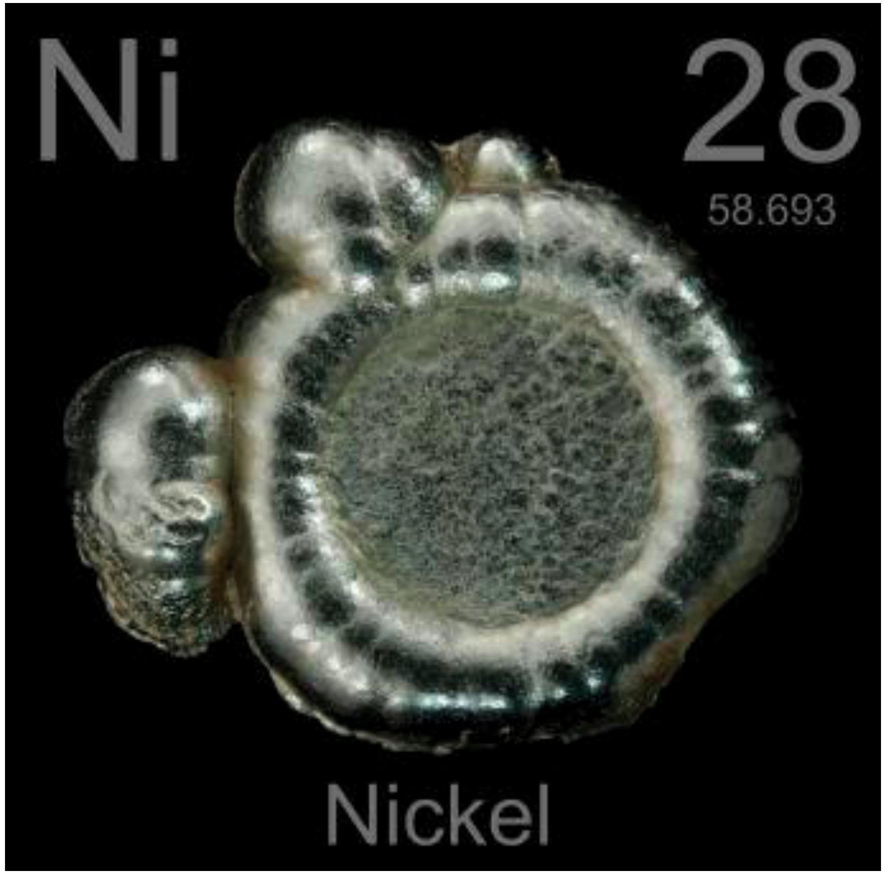
- Recent battery grade Li carbonate around $15,000/t
- About $2,500/t premium for producing $LiOH.H_2O$

Resourceful Paths

Lithium greenfield/expansion projects

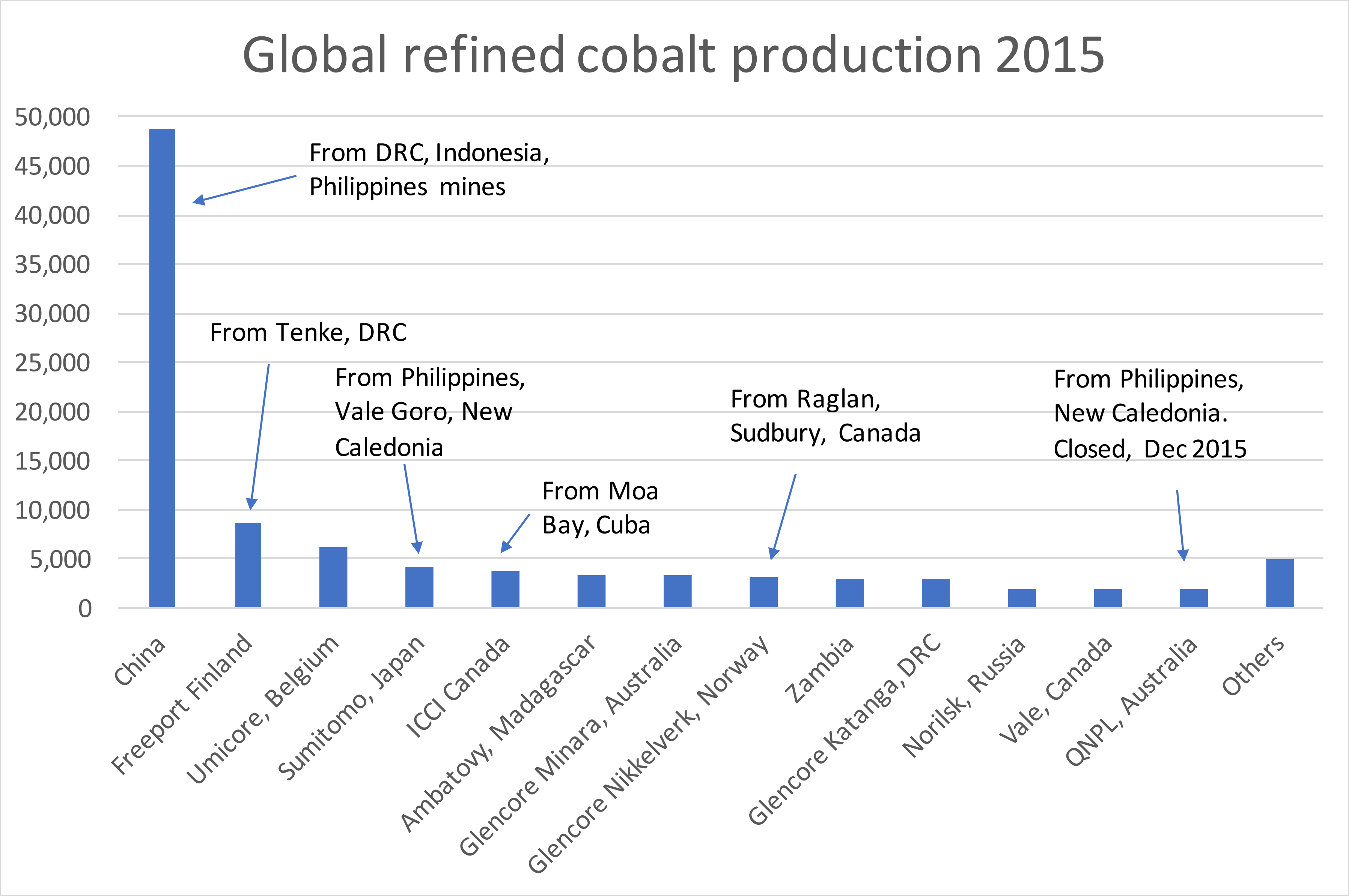
- Talison (Tianqi) - Salares 7, brine, Northern Chile
- Tianqi – battery grade LiOH plant in Kwinana, WA, converting spodumene concentrate from Greenbushes mine
- Galaxy Mount Cattlin, WA, spodumene concentrate
- Lithium Americas + SQM - Argentina
- Many juniors, some projects will fail
- Possibility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

Cobalt and nickel



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



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

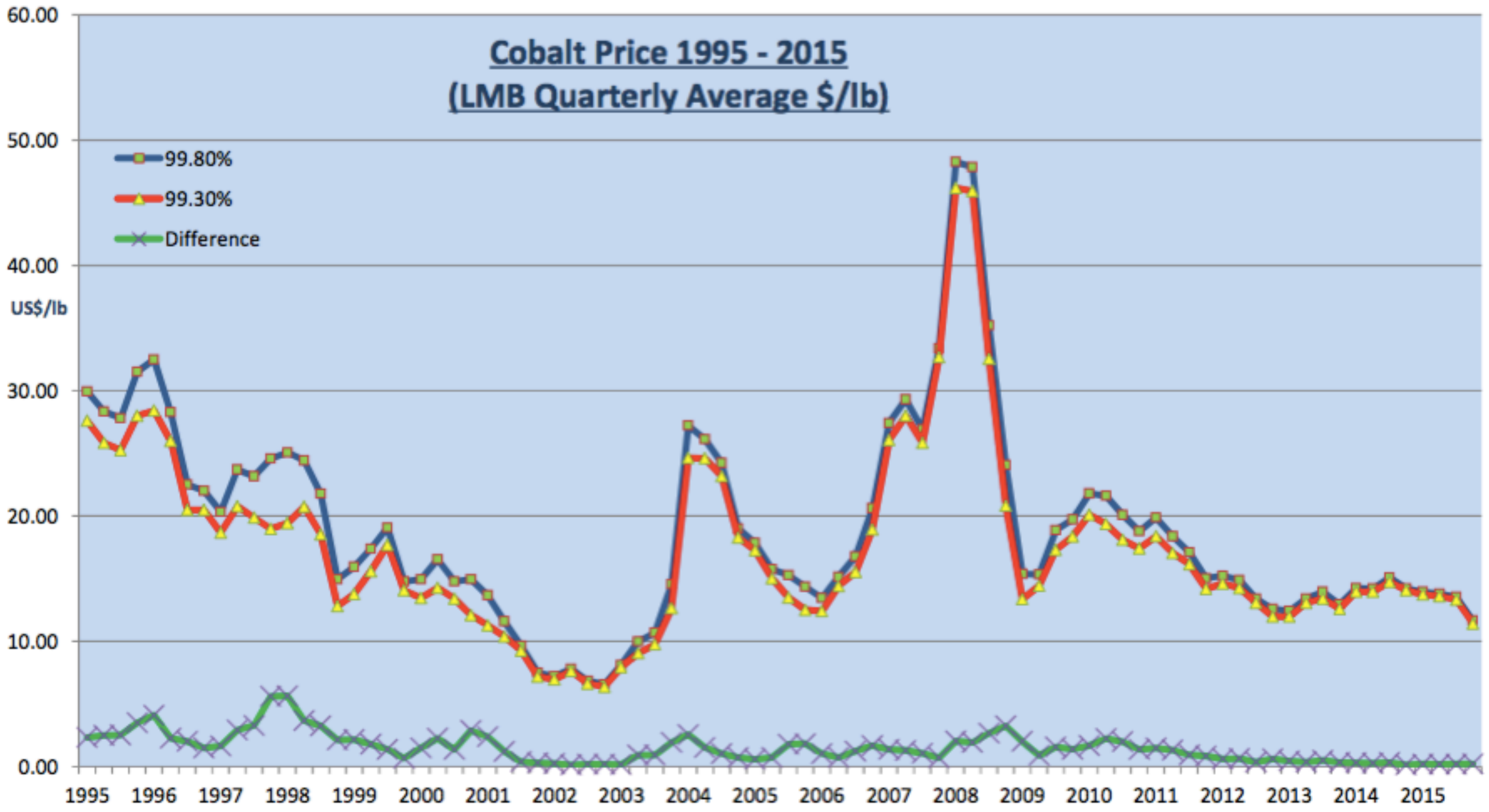
Source: Cobalt Development Institute, 2016

Cobalt prices back on the rise

- Co prices doubled in last year

Resourceful Paths

Cobalt prices back on the rise



- But not near the levels of 2008 yet

Source: Cobalt Development Institute, 2016

Major Cu-Co mines in DRC - Tenke

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.

Tenke Fungurume (100%)	Unit	2016
Copper Production	'000 Tonnes	224
Cobalt Production	'000 Tonnes	16

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

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

COMMODITIES | Mon May 9, 2016 | 10:12pm EDT

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

Glencore Buys Out Billionaire With $1 Billion Congo Mining Deal

Franz Wild, Jesse Riseborough and Thomas Wilson

February 13, 2017 at 6:26:58 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

Resourceful Paths

- 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

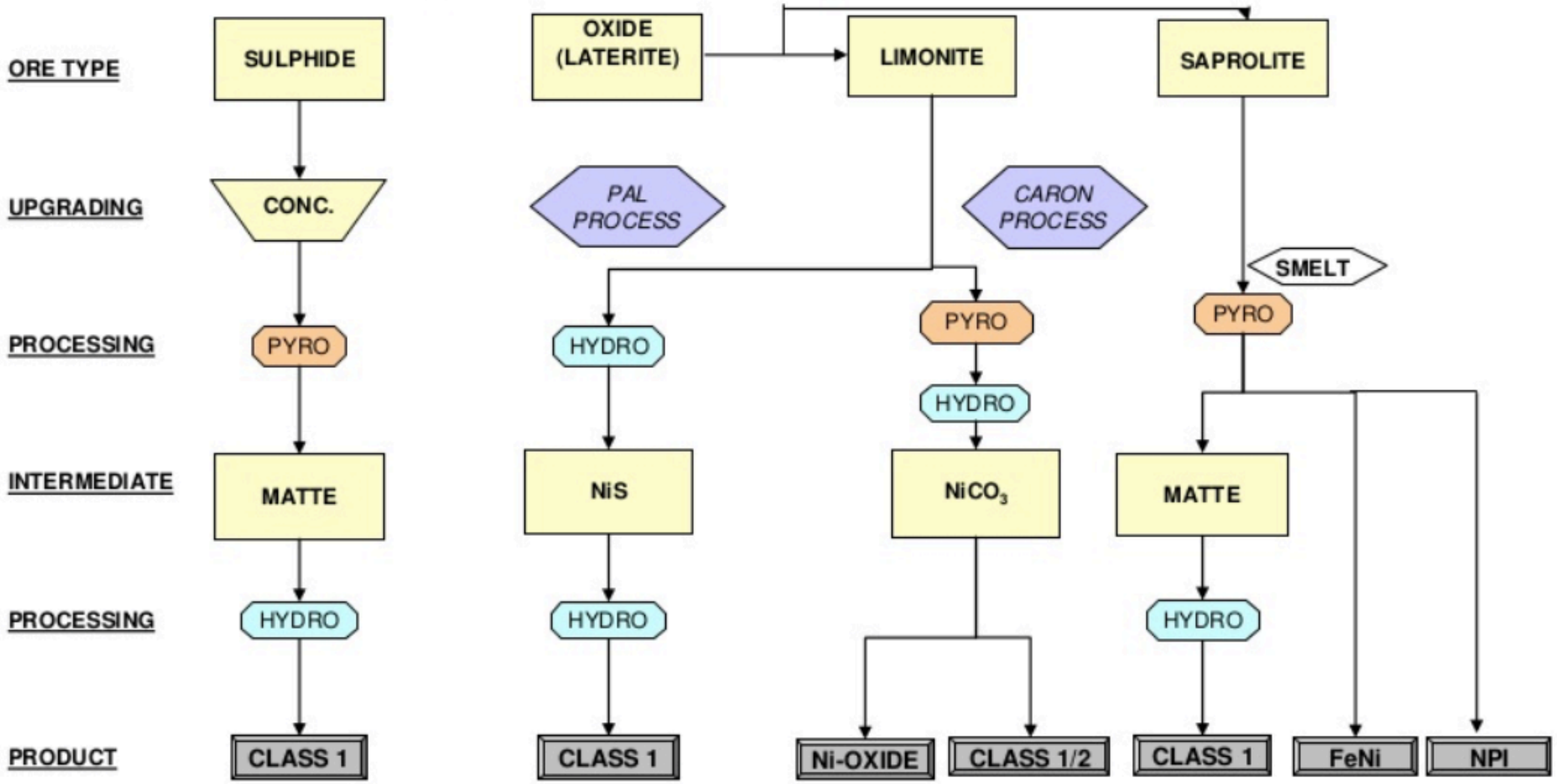
- Quantities hard to trace - middlemen and opaque trades
- Artisanal concentrates predominantly sold to China
- CRU estimate – artisanal miners in DRC produced concentrates containing 10,500 t Co, approx. 10% of global supply
- Estimated 100,000 artisanal miners in Katanga region of DRC, many are women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

Source: http://www.crugroup.com/about-cru/cruinsight/DRC-Artisanal-Cobalt-Industry

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



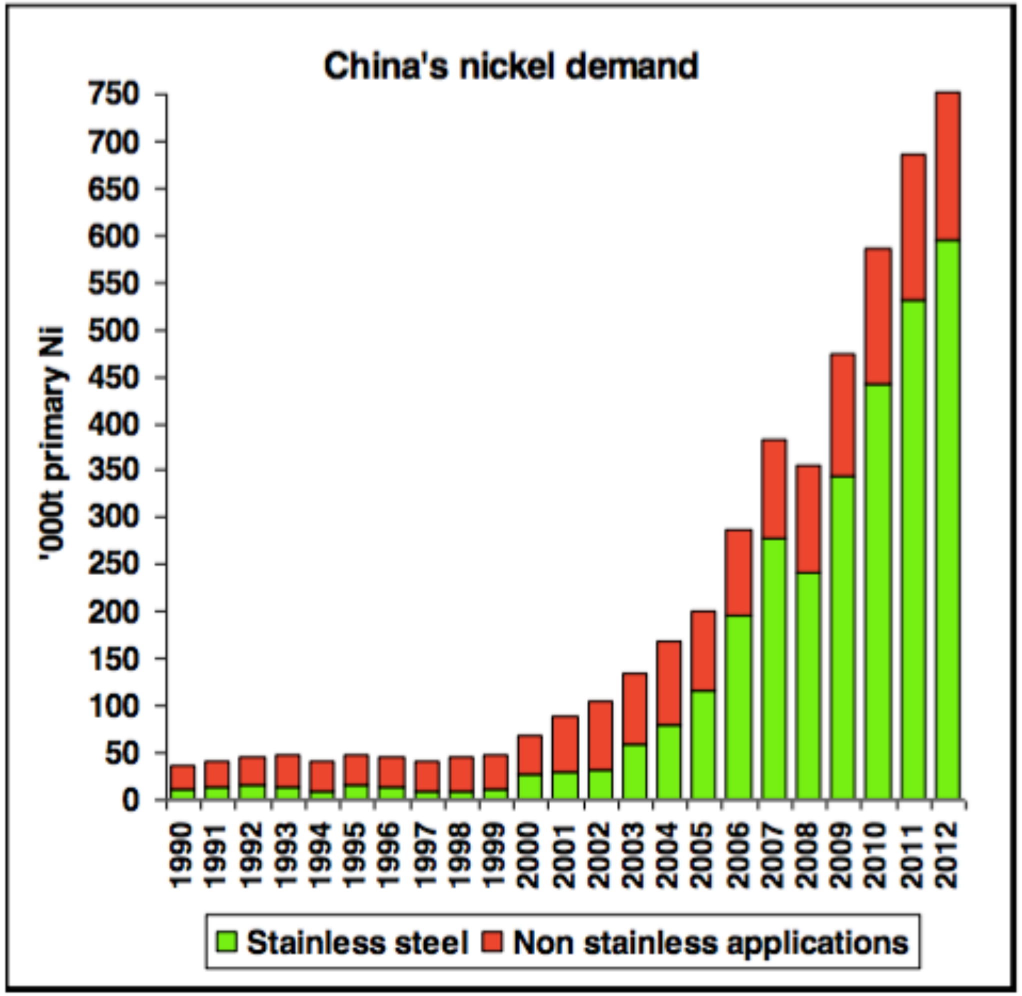
Source: INSG, Macquarie Research, July 2013

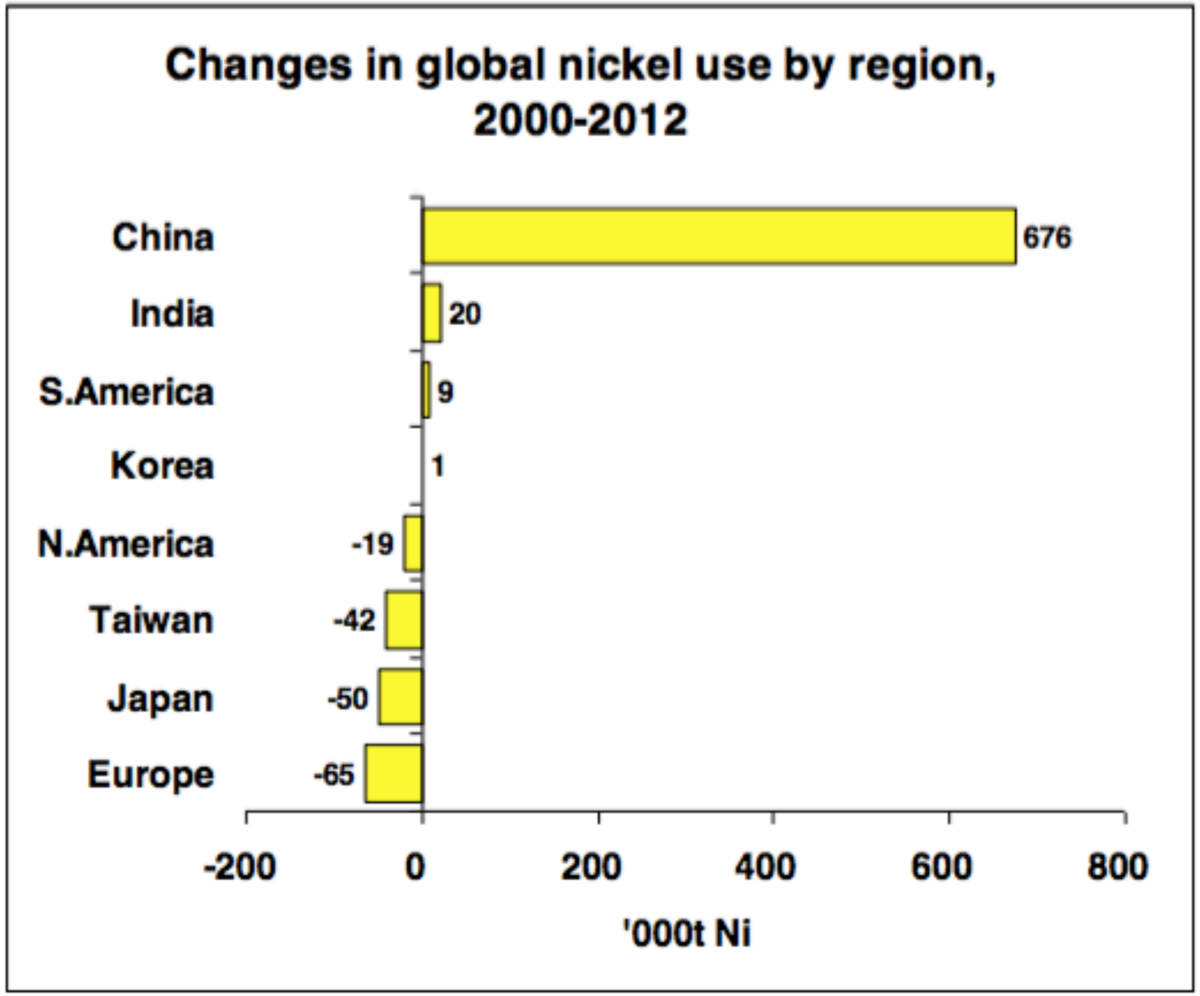
Note: excludes leaching processes for sulphides (Talvivaara bioleach in Finland) and limonites (in Guangxi and Jiangshi in China)

Source: Macquarie Commodities Research, 2013

Resourceful Paths

Ni use - stainless steel and China

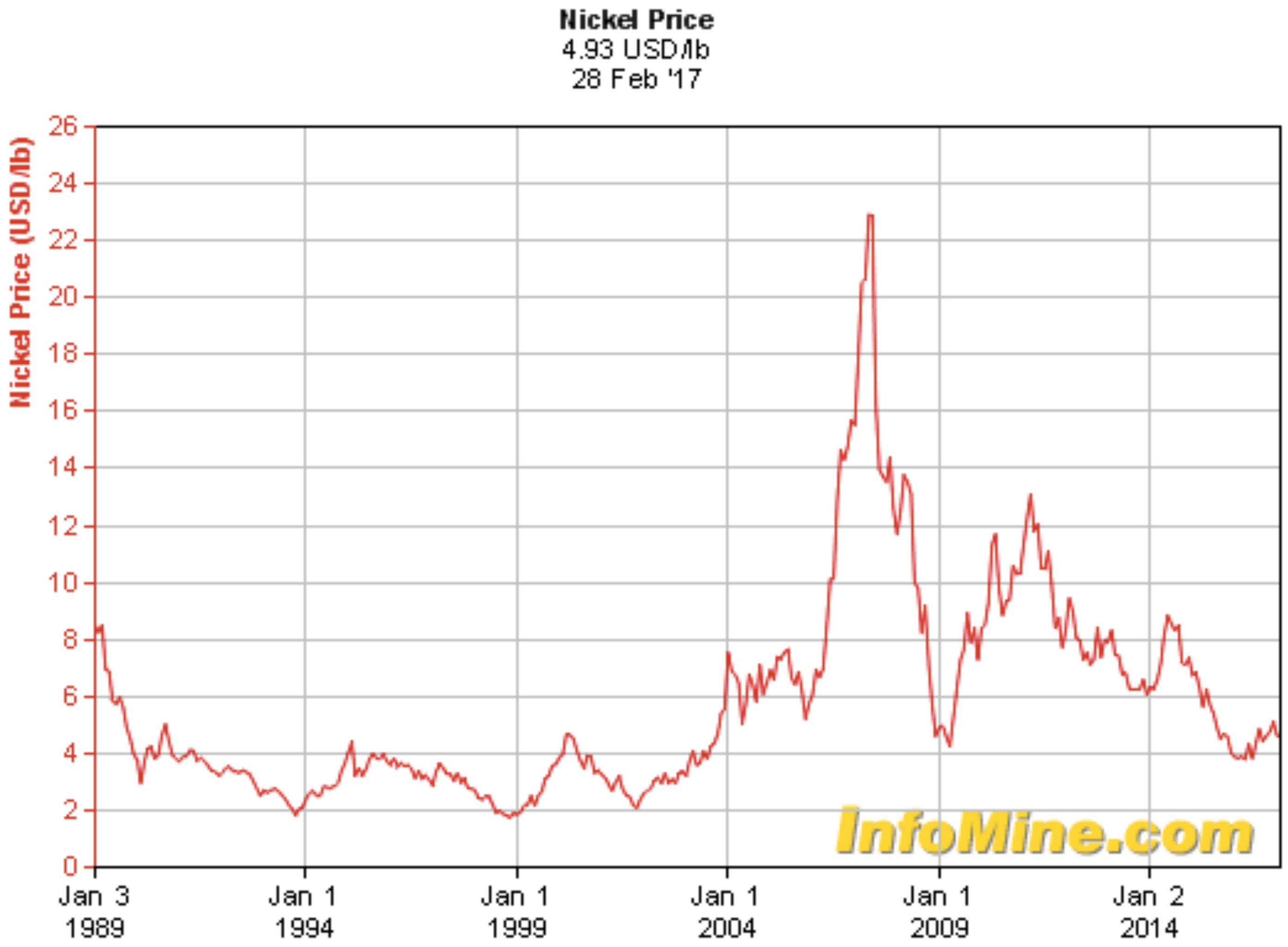




Source: Macquarie Commodities Research, 2013

Ni prices in the doldrums

Resourceful Paths



Asian export bans – Ni uncertainty

Resourceful Paths

- 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

Resourceful Paths

Indonesia, Philippines mining bans

ASIA TIMES EST 1995

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

By JOEL ADRIANO | MANILA, MARCH 1, 2017 3:36 PM (UTC+8)

The Economist

Shafted

Indonesia and the Philippines hobble the mining industry

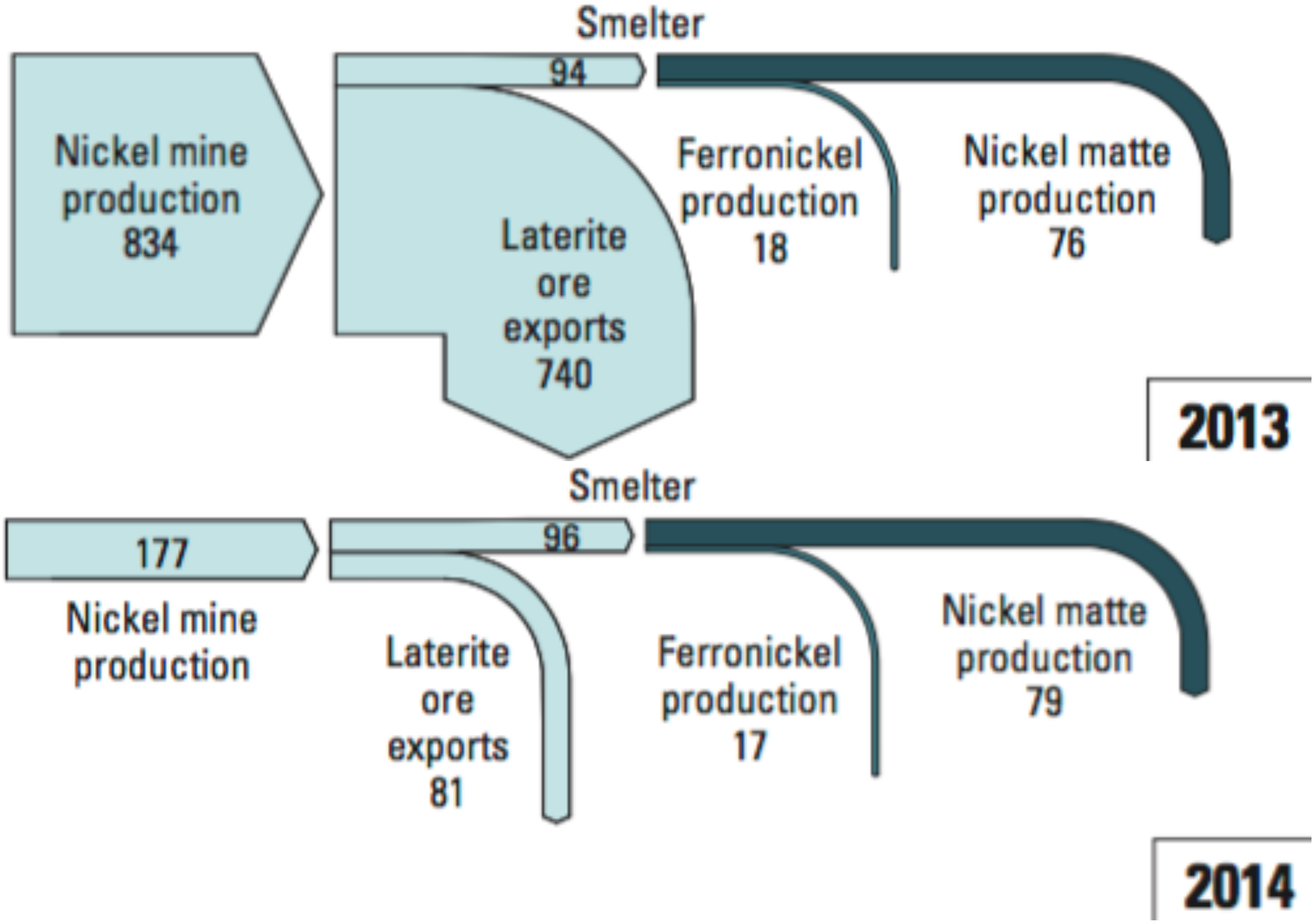
Jobs and revenue evaporate as the regulators pile on

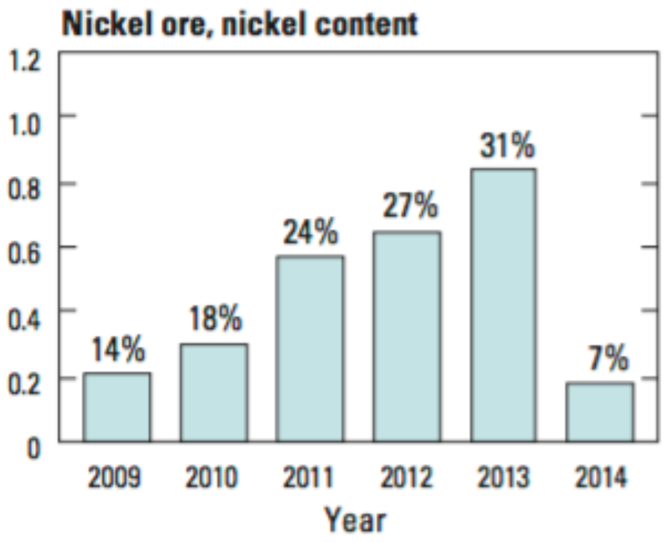
From the print edition | Asia

Feb 23rd 2017 | JAKARTA AND MANILA

Indonesian export bans

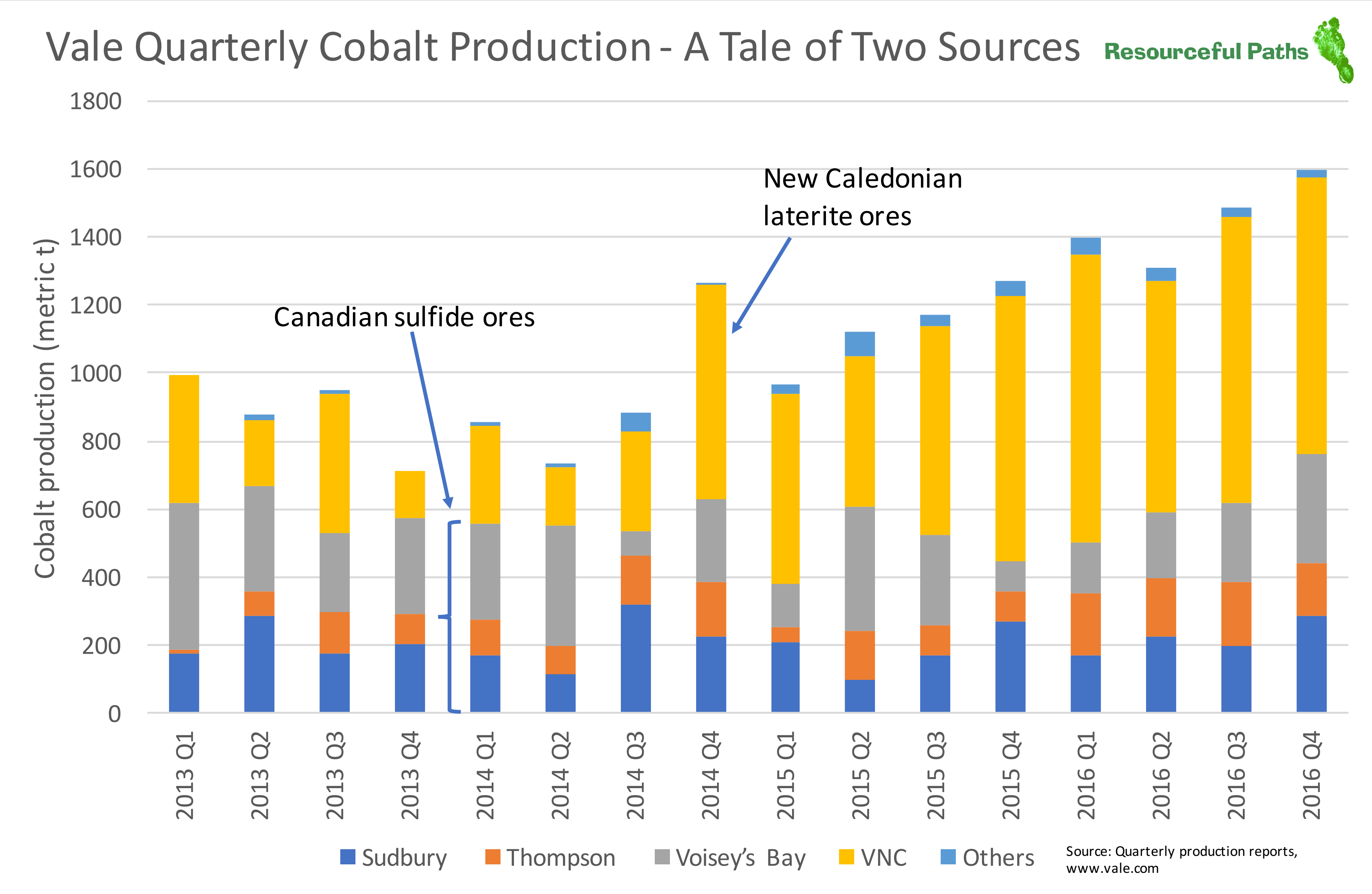
Resourceful Paths





- 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

Co and Ni from laterites

Ambotovy

Goro

- Complex, multibillion $ plants, struggling to pay their way

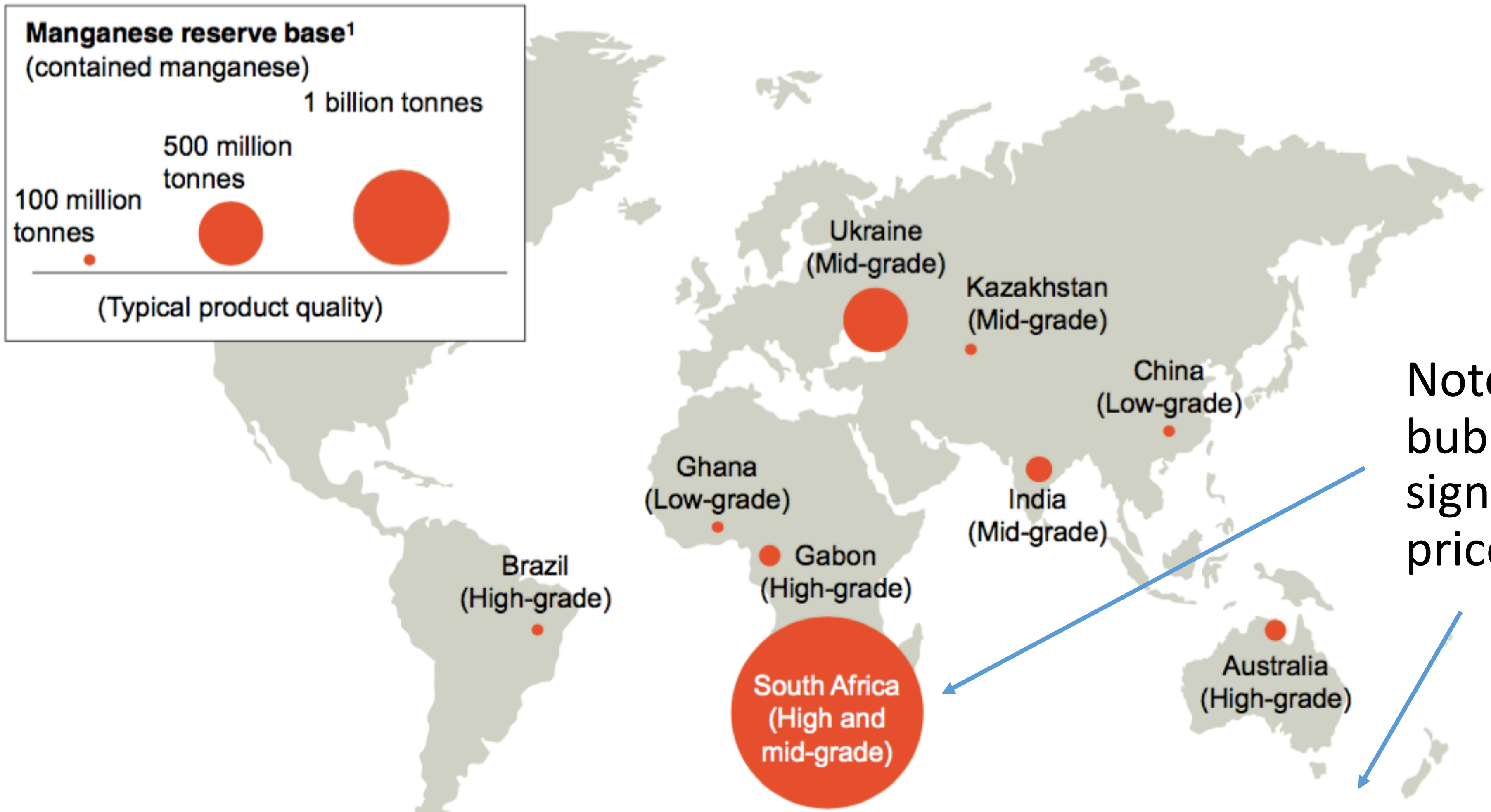
Co from Ni laterite refining

Resourceful Paths

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

Manganese

Mn resources – South Africa #1



1. Defined by the US Geological Survey (USGS) as that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources).

Source: BHP Billiton analysis, Roskill 2012, USGS

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

Resourceful Paths

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 MnO_2 (EMD)
  - Rare earth elements
- Implications - mining value chain, supply chain transparency

Resourceful Paths

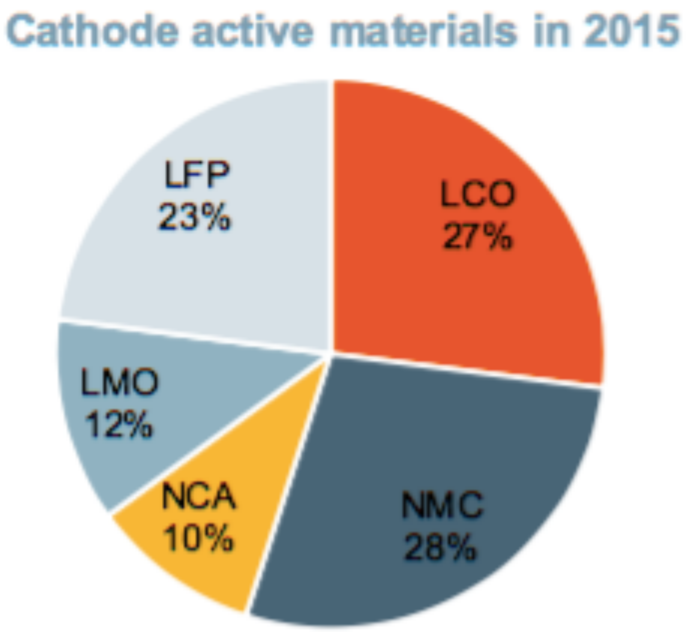
Co, Ni needs - different chemistries

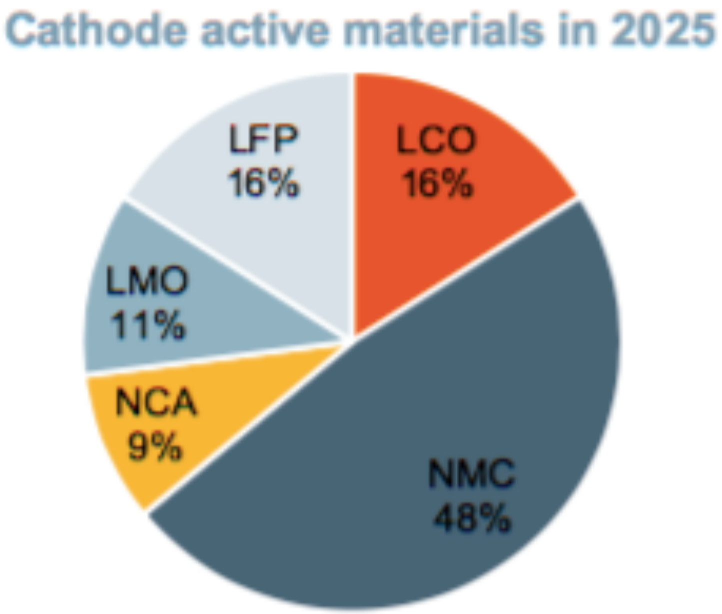
Battery type	Cathode stoichiometry	Weight ratio - cathode	
		Co:Li	Ni:Li
LCO	$LiCoO_2$	8.5	0.0
NMC – equal ratios	$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$	2.8	2.8
NMC – low Co	$LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$	1.7	3.4
NCA	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	1.2	6.8
LMO	$LiMn_2O_4$	0.0	0.0
LFP	$LiFePO_4$	0.0	0.0

- 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

Resourceful Paths

- 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

FINANCIAL POST

RB Energy shutters Quebec lithium mine as financing fails

Peter Koven | October 8, 2014 4:36 PM ET
More from Peter Koven | @peterkoven

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- Despite lithium story, advanced projects can fail due to processing and logistics complexities

What to do at end of Pb?

Resourceful Paths

- 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?

Resourceful Paths

Can't control	Can control
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

Resourceful Paths

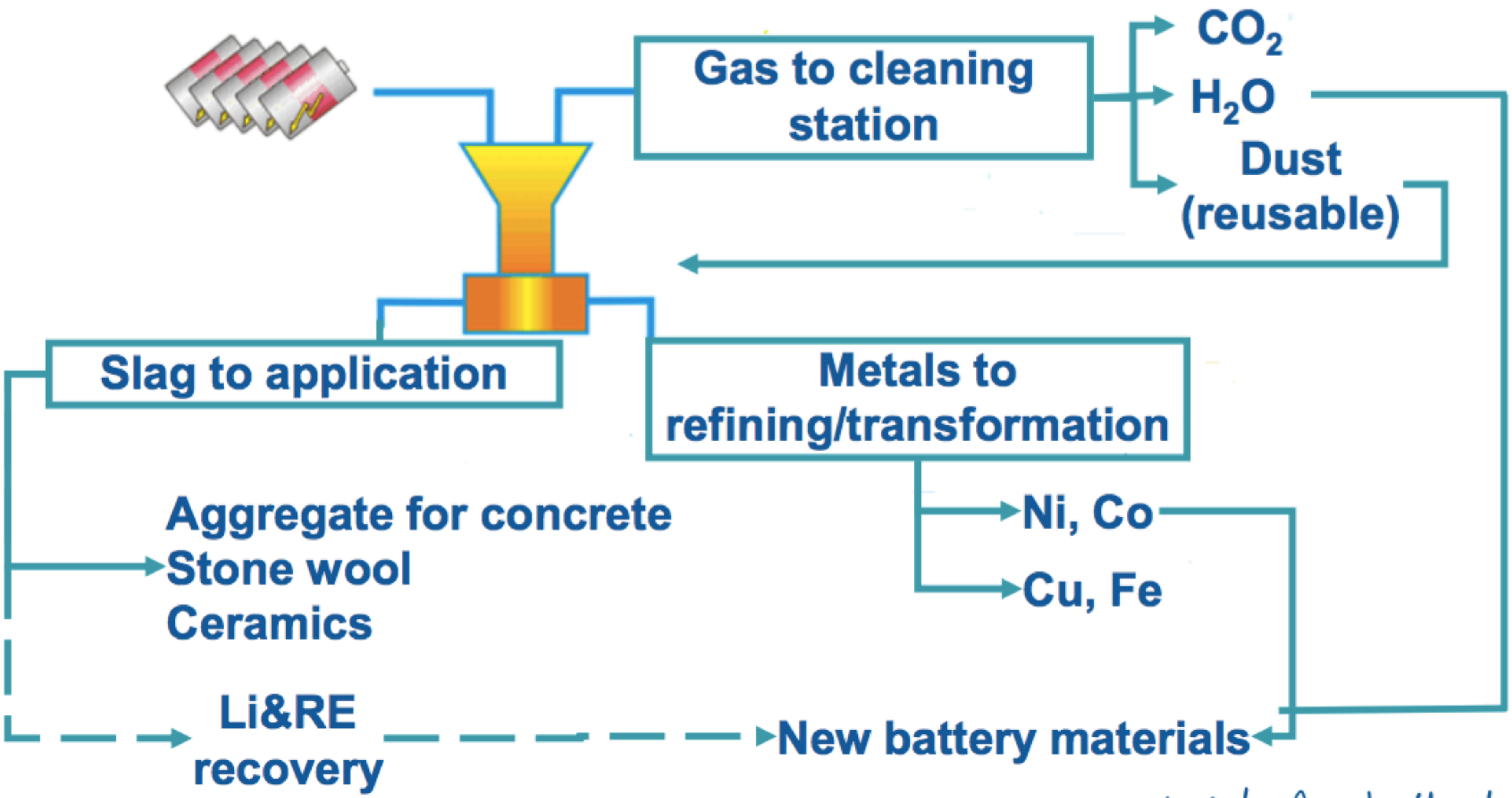
Li battery ingredients comparison

	Li	Co	Ni	Mn	Al	Fe
Crustal abundance rank	33	32	24	12	3	4
Current main mine producers	Australia, Chile	DRC	Philippines, Russia, Canada	South Africa, Australia	Australia, China, Brazil	Australia, Brazil, China
Main refiners	China	China	China	China	China	China
Supply chain risk	Low	High	Moderate	Low	Low	Low

Circular economy

Umicore – integrated battery recycling

Resourceful Paths



LiB-NiMH recycling at Umicore 8 materials for a better life

Jan Tytgat

Conclusions

Conclusions

Resourceful Paths

- 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