Risk within Materials Supply Chains for Transportation

This is the work of…

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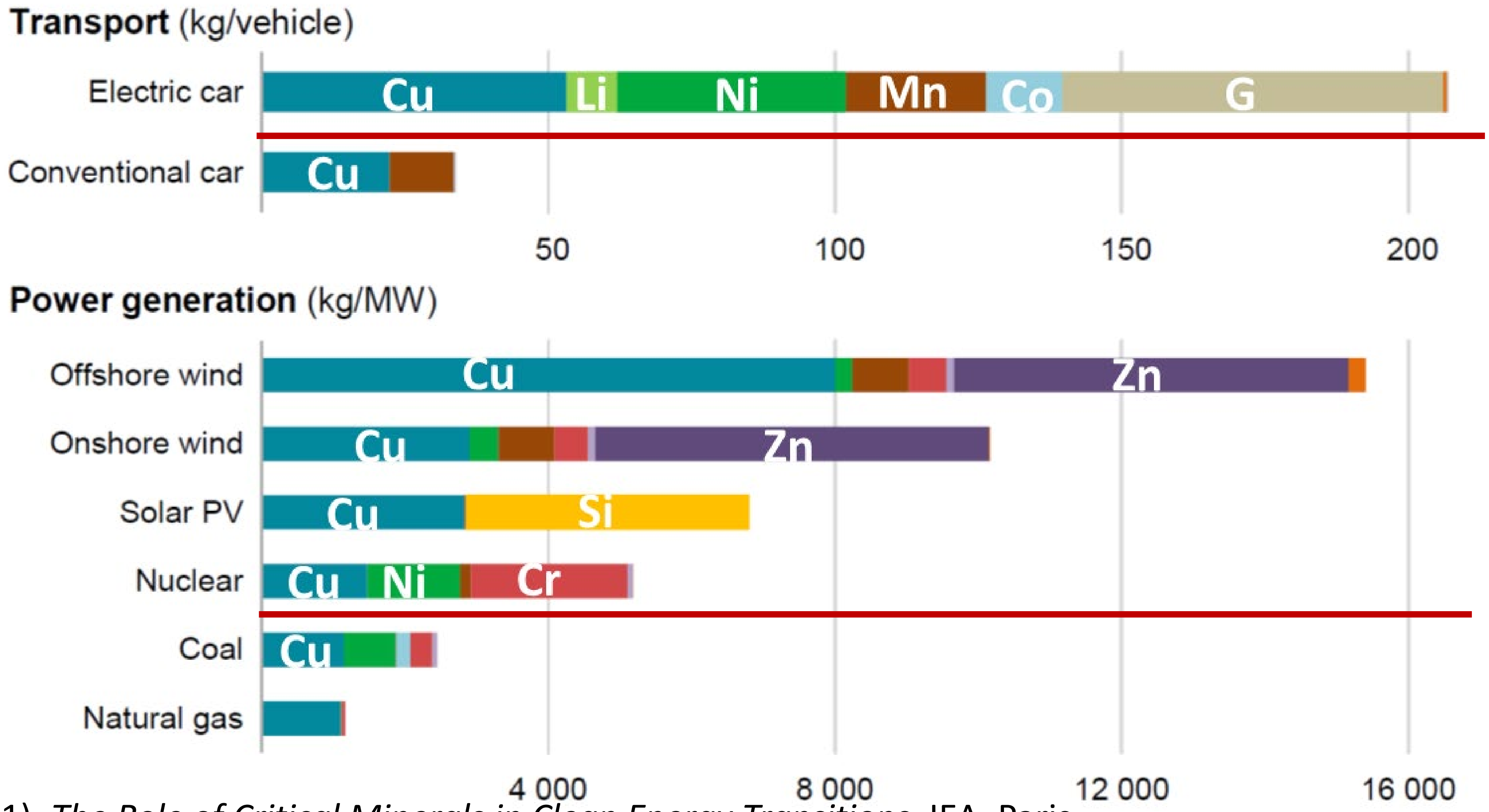
Rapid deployment of energy transition technologies implies a significant increase in demand for minerals.

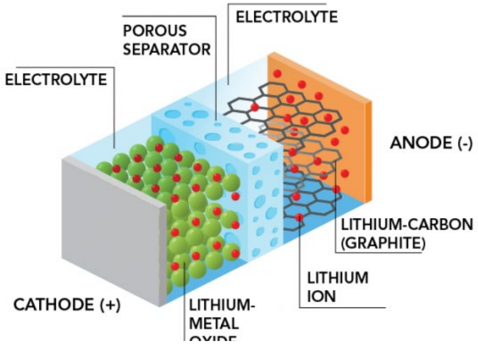


IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*, IEA, Paris
https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions, License: CC BY 4.0

Technologies across many areas in transportation will require more and better materials to address current societal challenges

Batteries

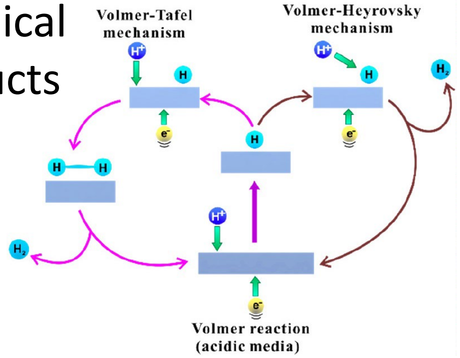
Energy storage



Catalysts

Electrofuels

Chemical products



Alloy design

Lightweighting

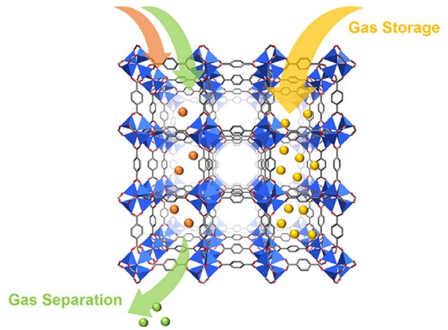
Recyclability

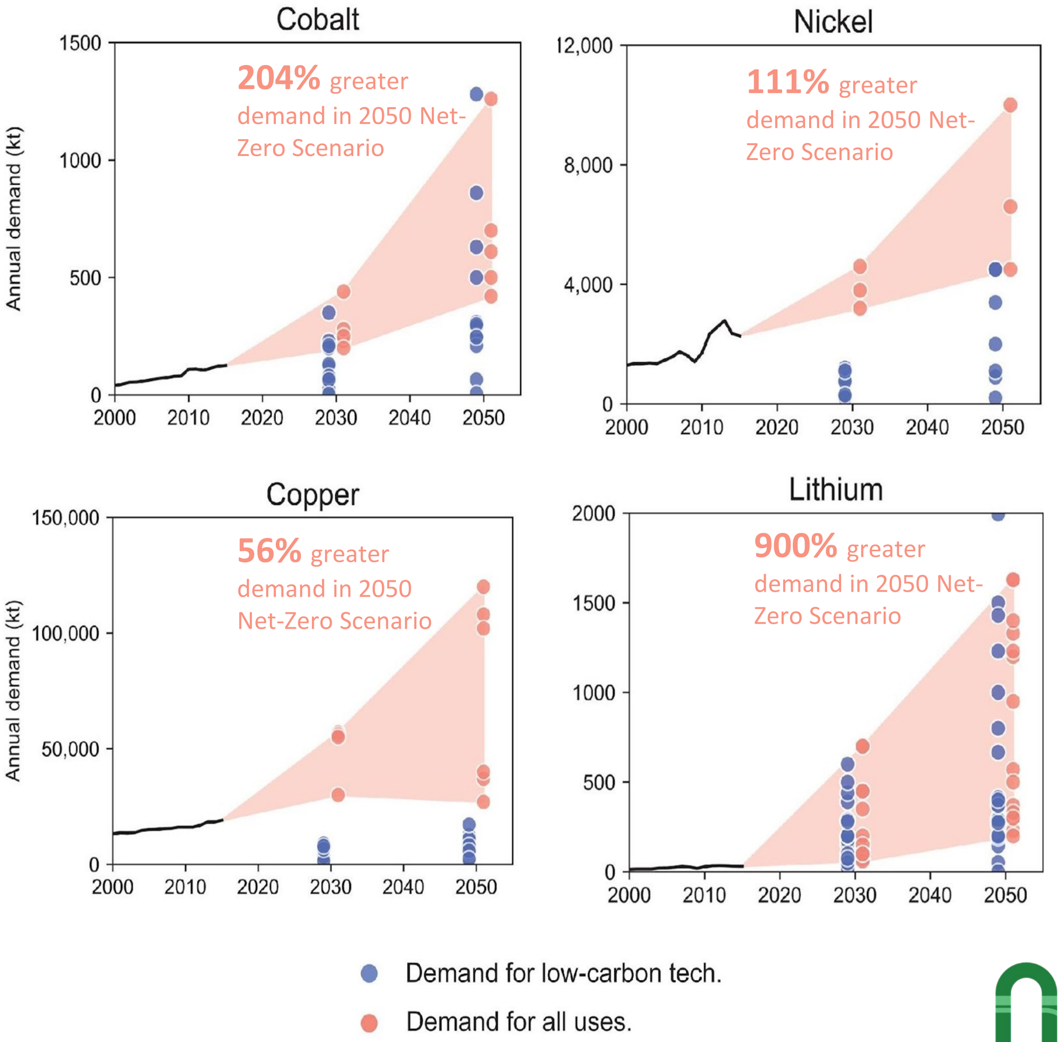
Durability

Gas storage

Carbon capture

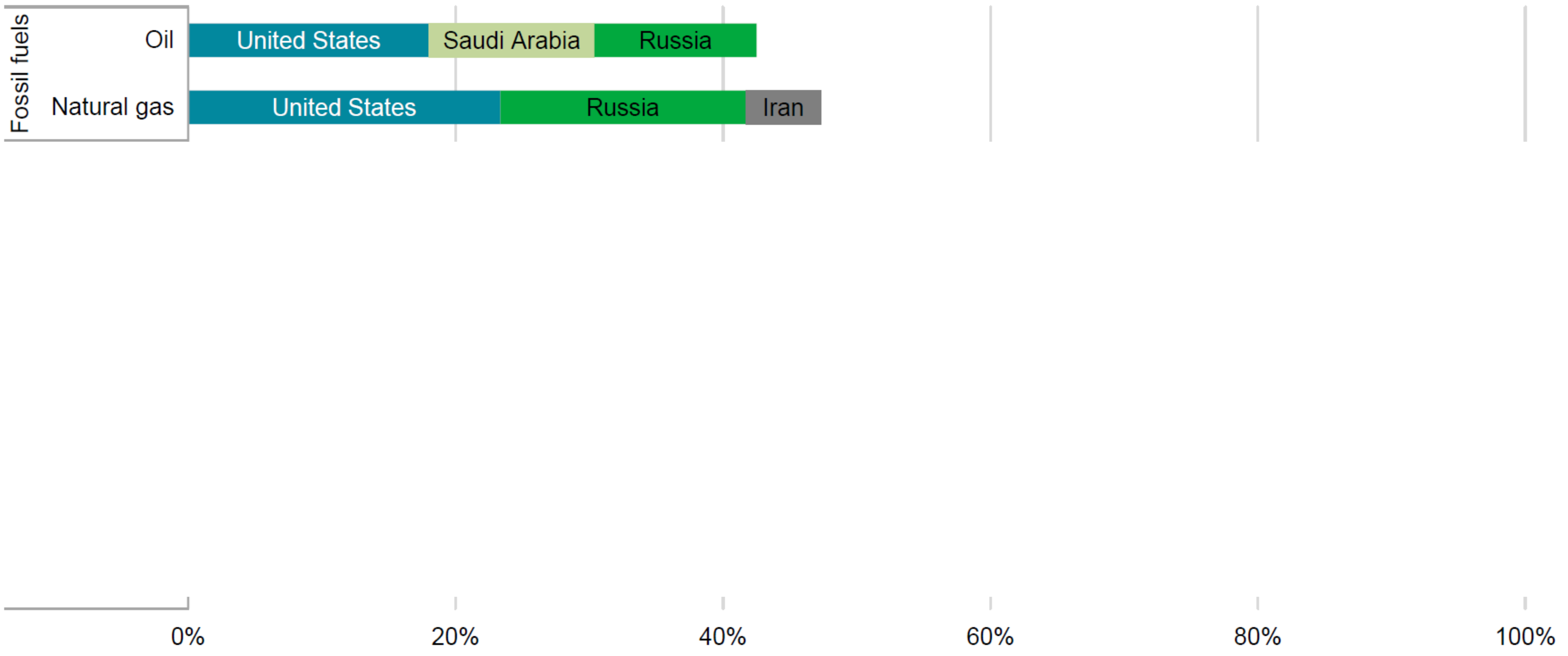
Hydrogen storage





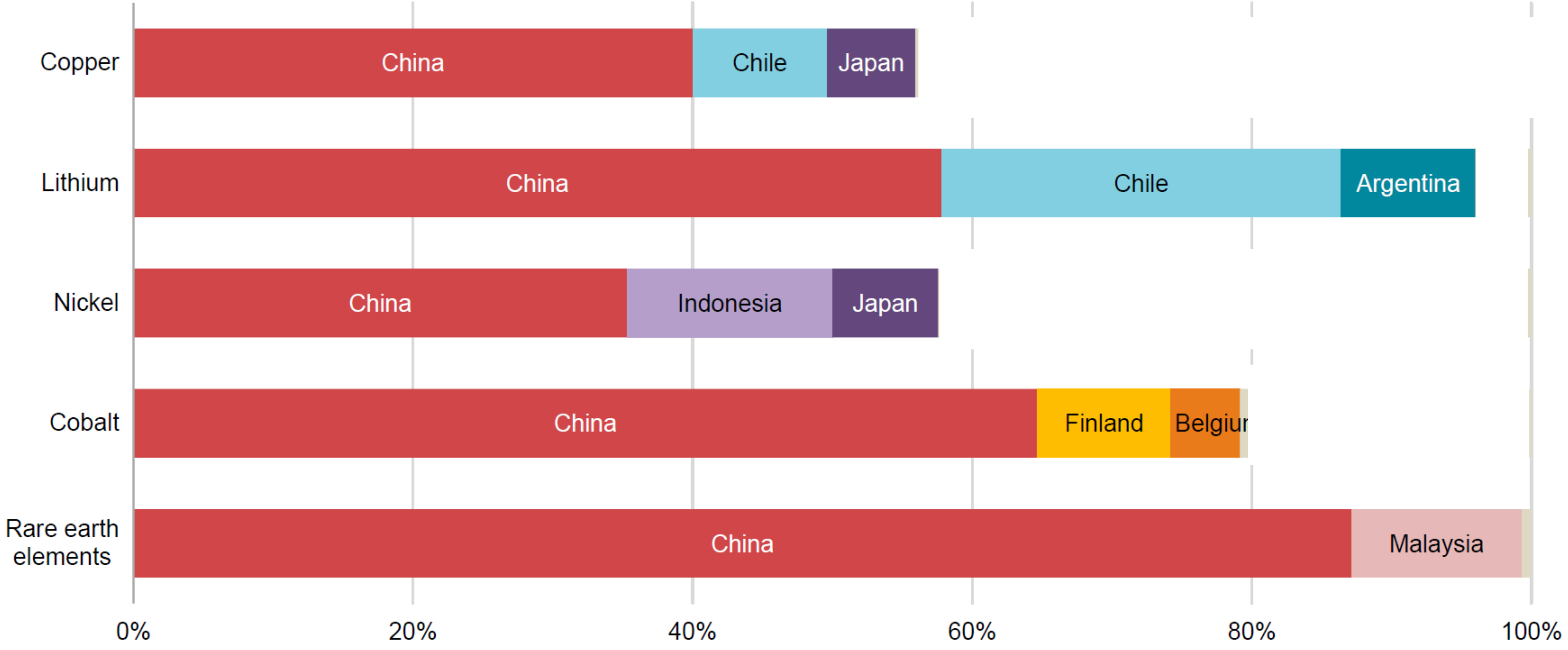
Watari (2020) "Review of critical metal dynamics to 2050 for 48 elements"

Share of top producing countries in production of fossil fuels and selected minerals



IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*, IEA, Paris
https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions, License: CC BY 4.0

Share of processing volume by country for selected minerals

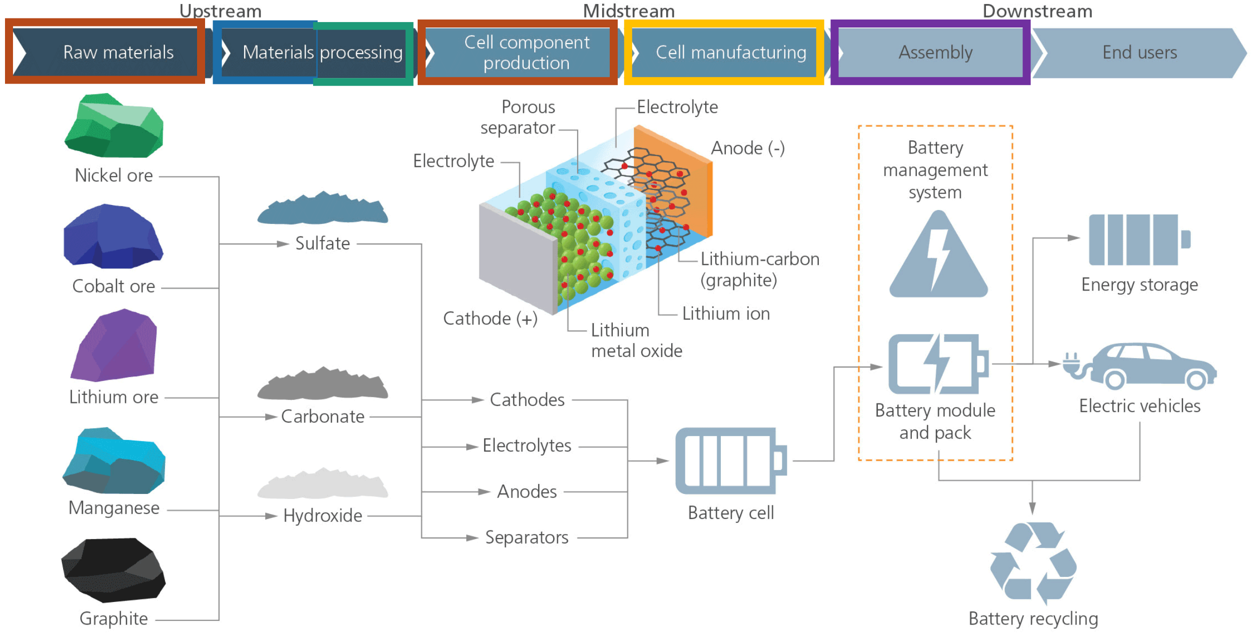


IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*, IEA, Paris
https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions, License: CC BY 4.0

Battery supply chains traverse extensive geographies

miles
4,800
+
7,500
+
1,250
+
200
+
6,500
=
~20,000

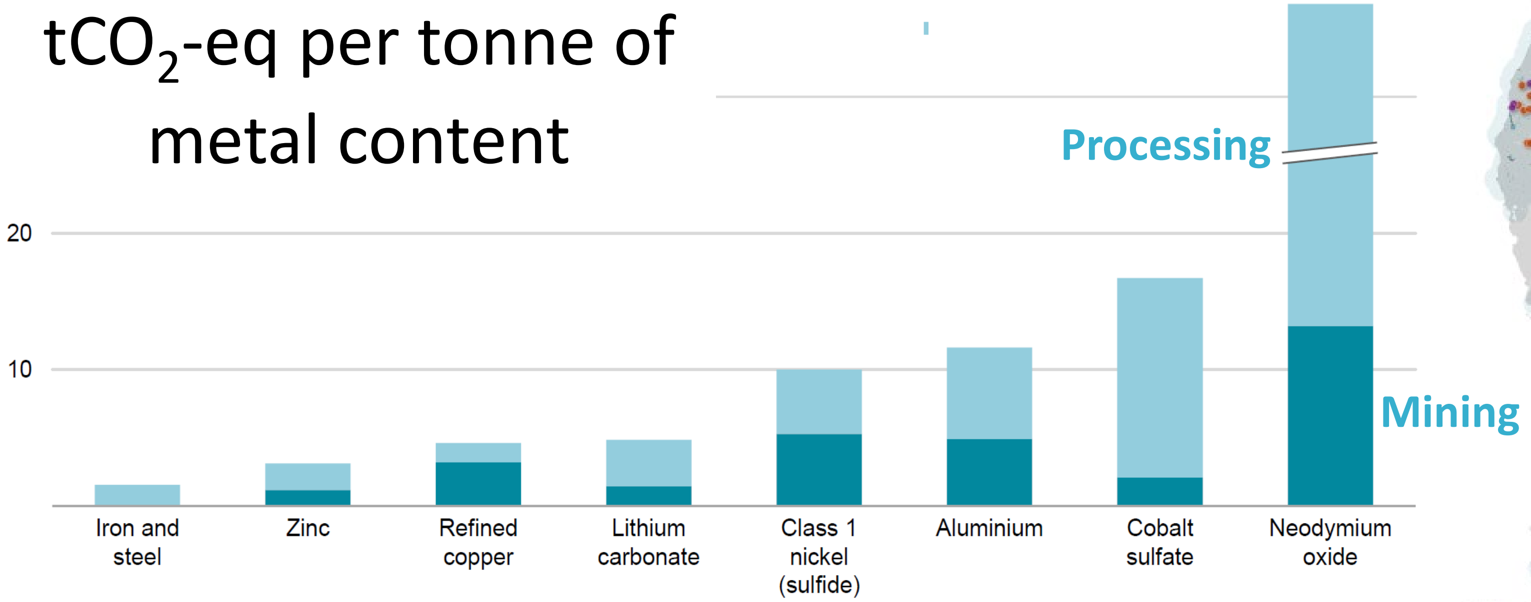
Battery is shipped back to Los Angeles to be incorporated into car battery pack



Source: L.E.K. research and analysis

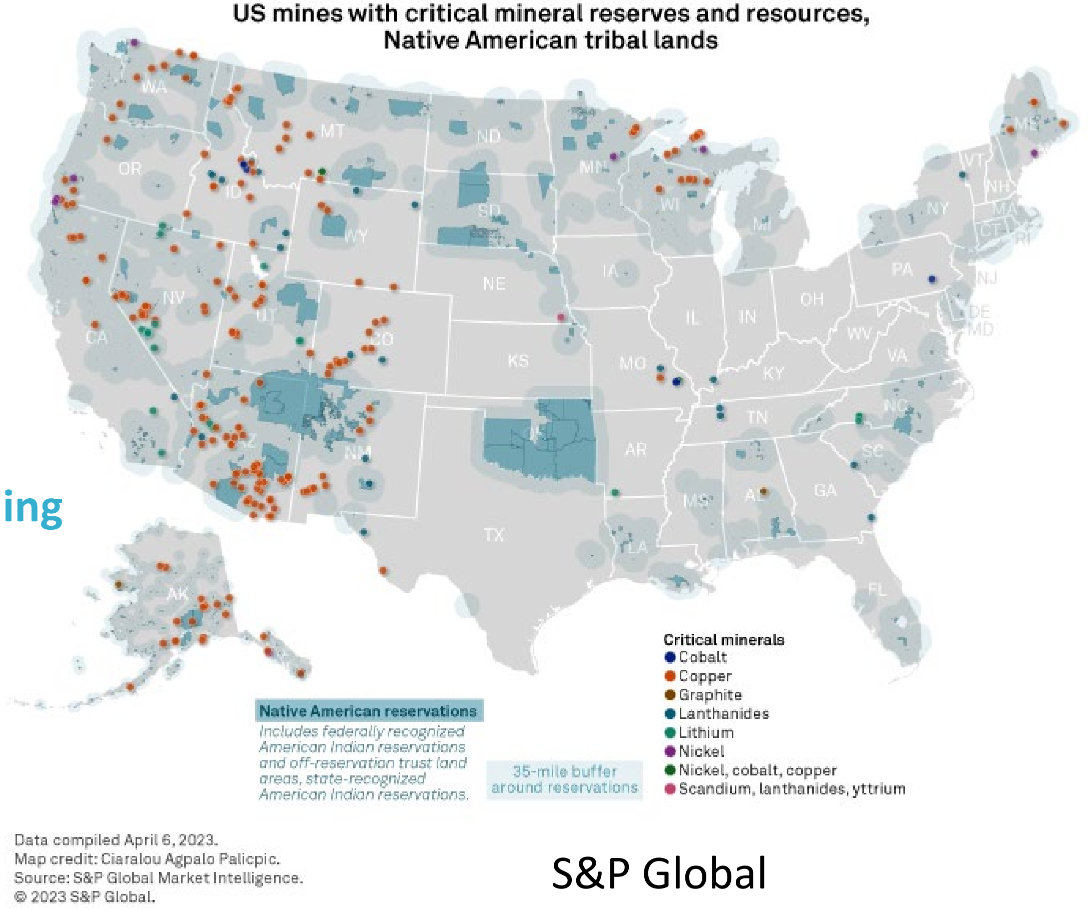
Changing patters of demand and types of resources lead to more significant environmental and social burdens

tCO$_2$-eq per tonne of metal content



Technology	kgCO$_2$-eq/kg Ni
Sulfide (today!)	5-10
Alternative process	20-30
Alternative ore	50-60

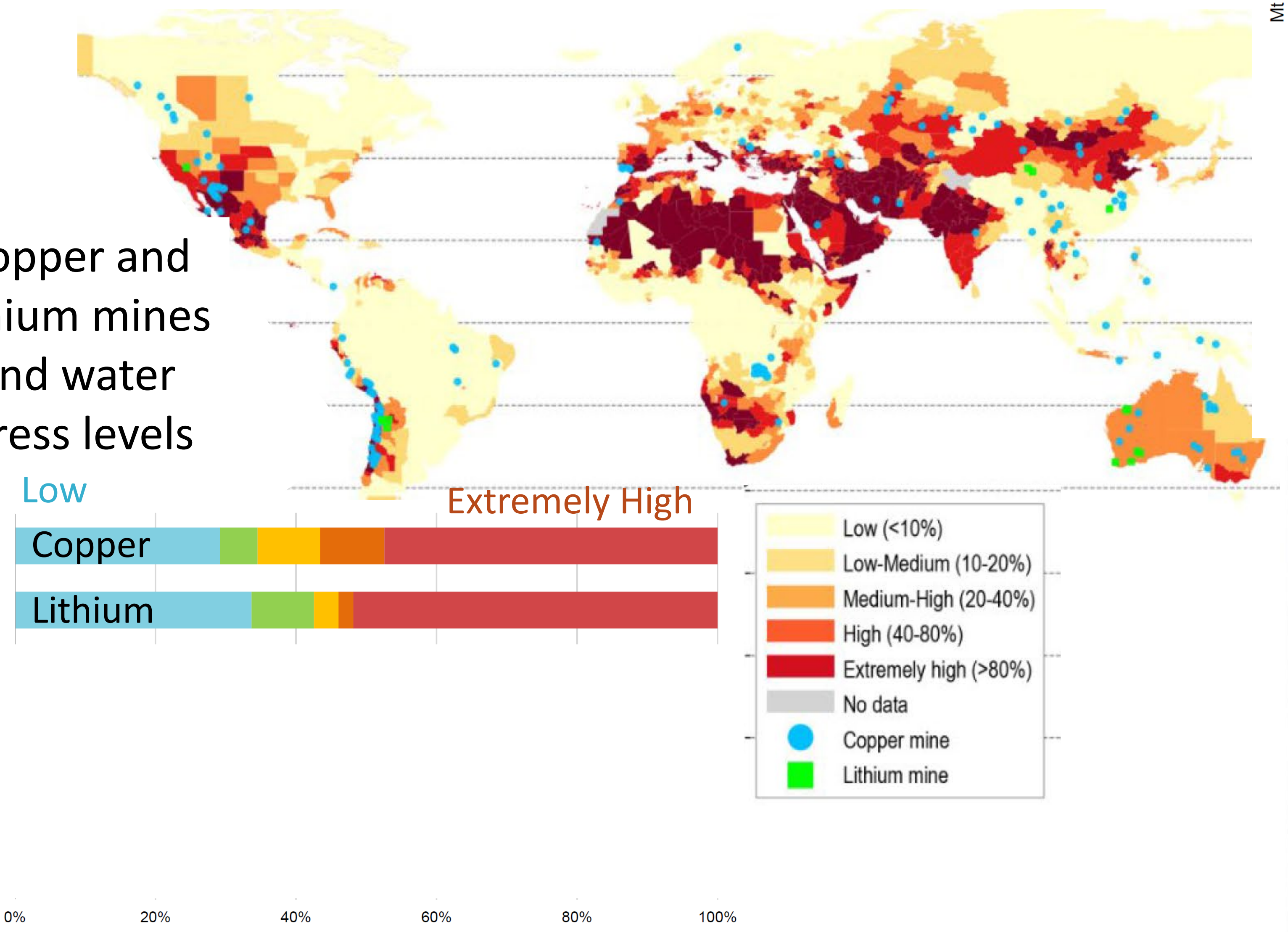
Ullman (2004)



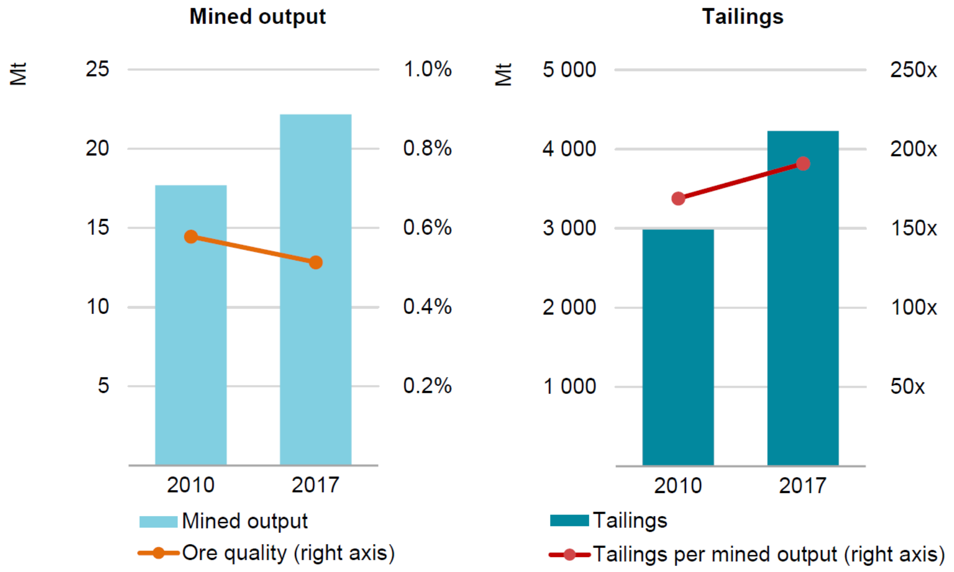
S&P Global Intelligence

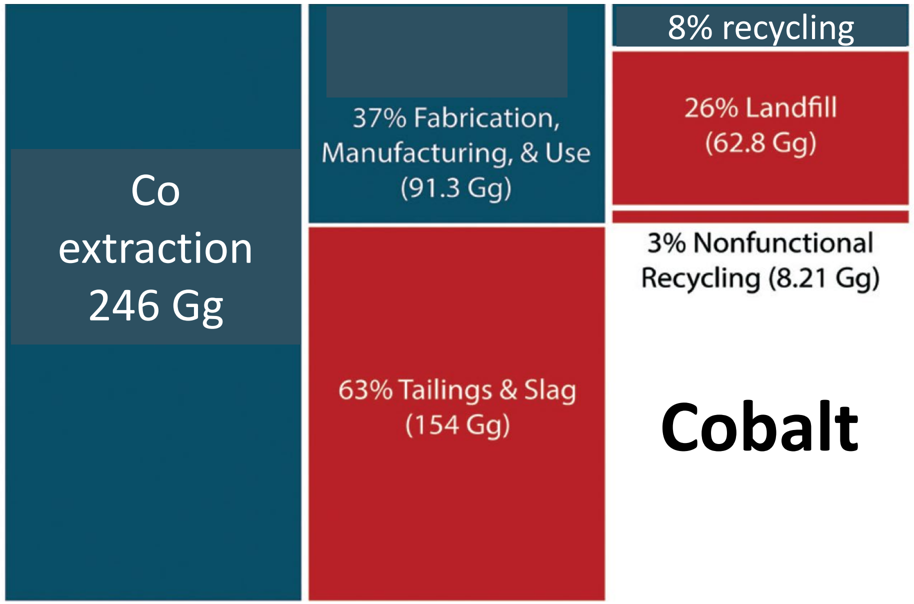
Environmental risk goes far beyond GHG emissions: Land use, water stress and waste

Copper and lithium mines and water stress levels

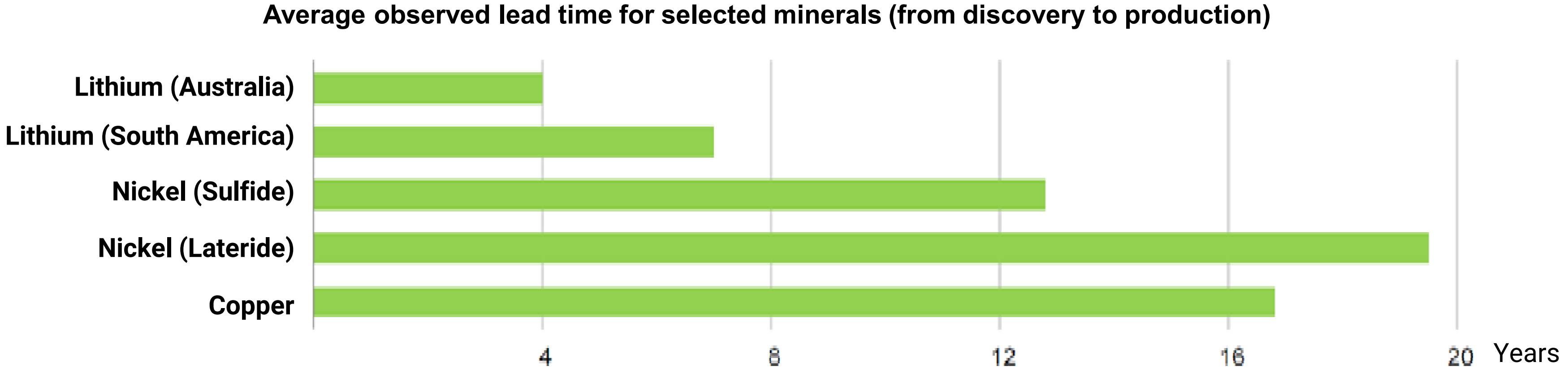


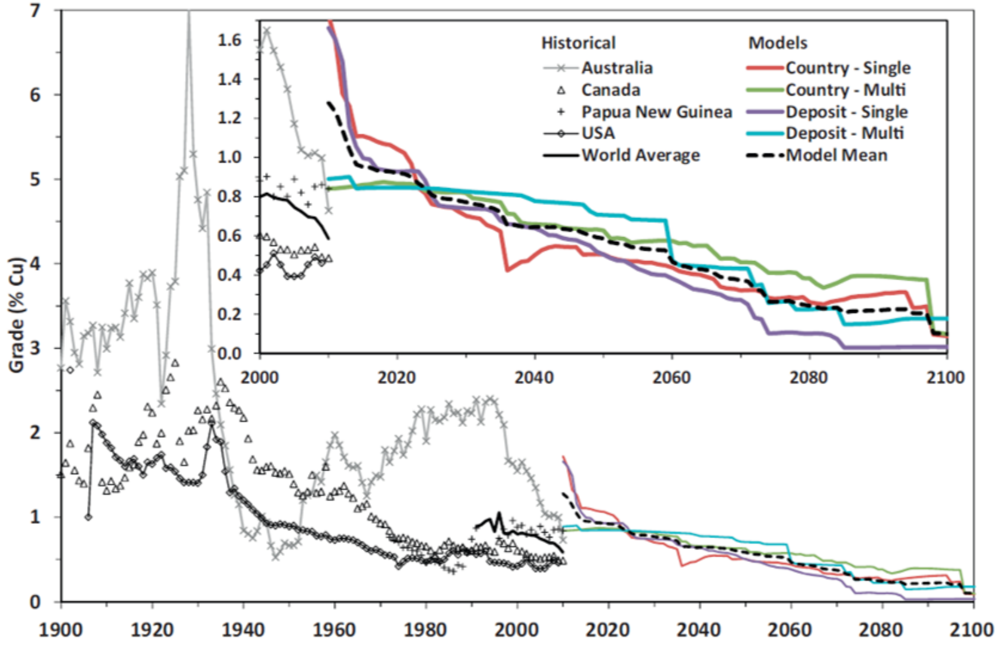
Waste generation from copper and nickel mining

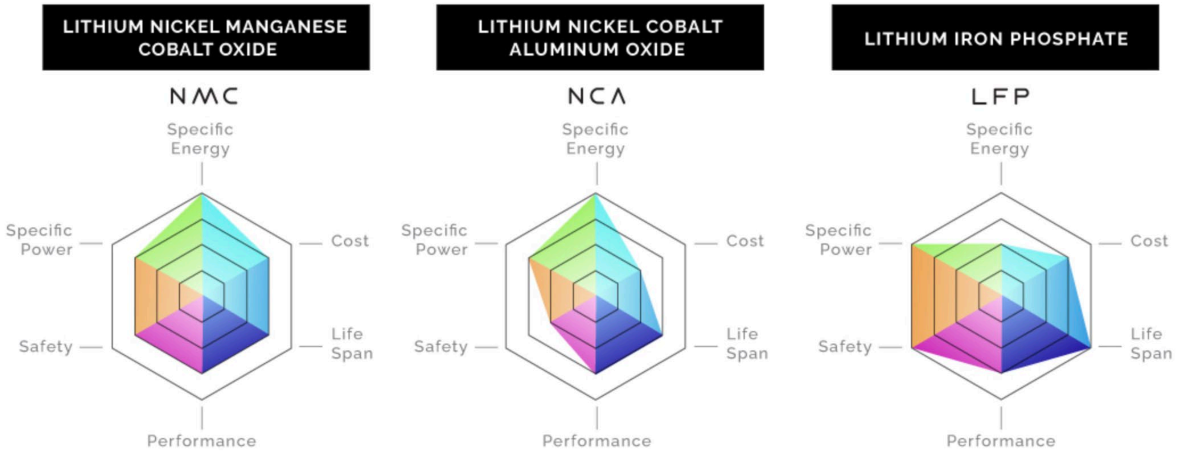




Our low-carbon future is mineral intensive: This creates tensions and tradeoffs that require systems-based, scalable, cross-discipline solutions







Even within NMC chemistries, cobalt content varies by a factor of 4

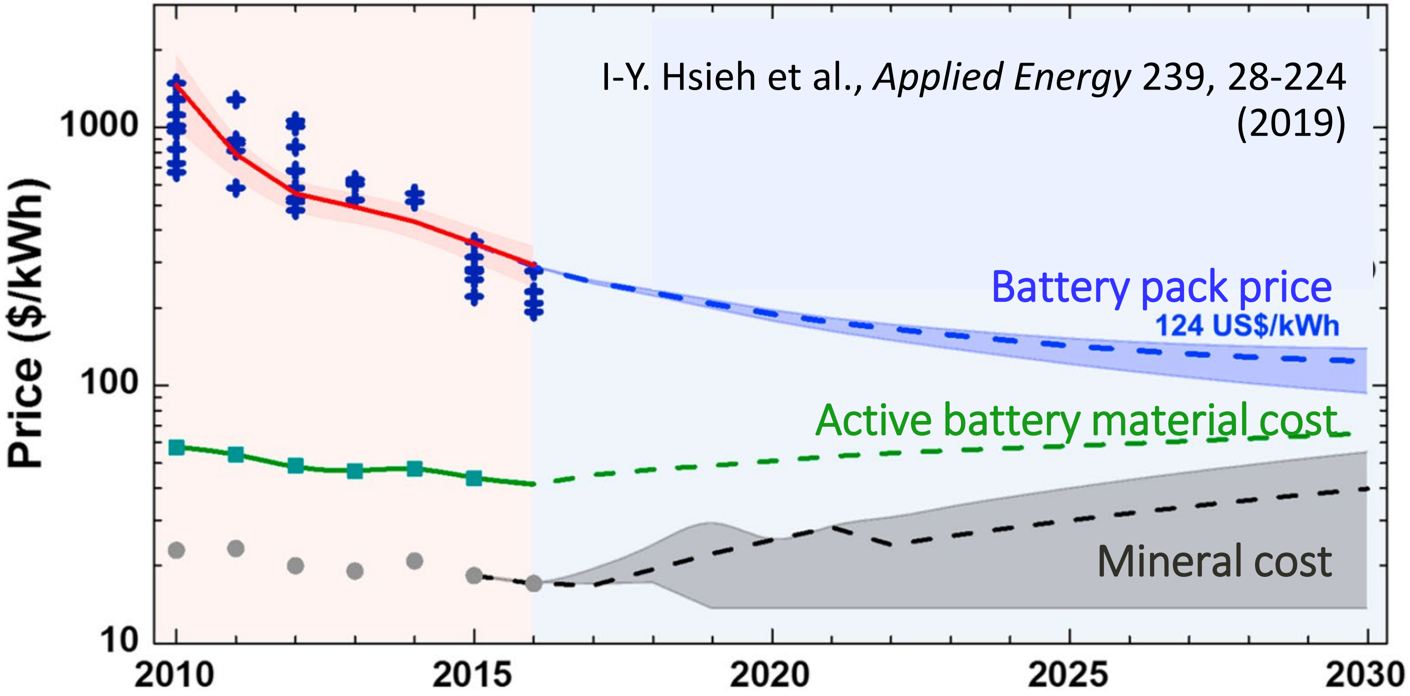
Figure from https://elements.visualcapitalist.com/the-six-major-types-of-lithium-ion-batteries/

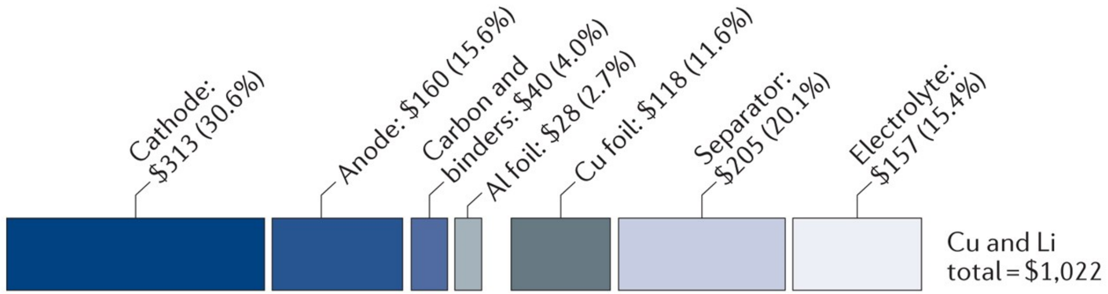
How does materials availability map to your current job?

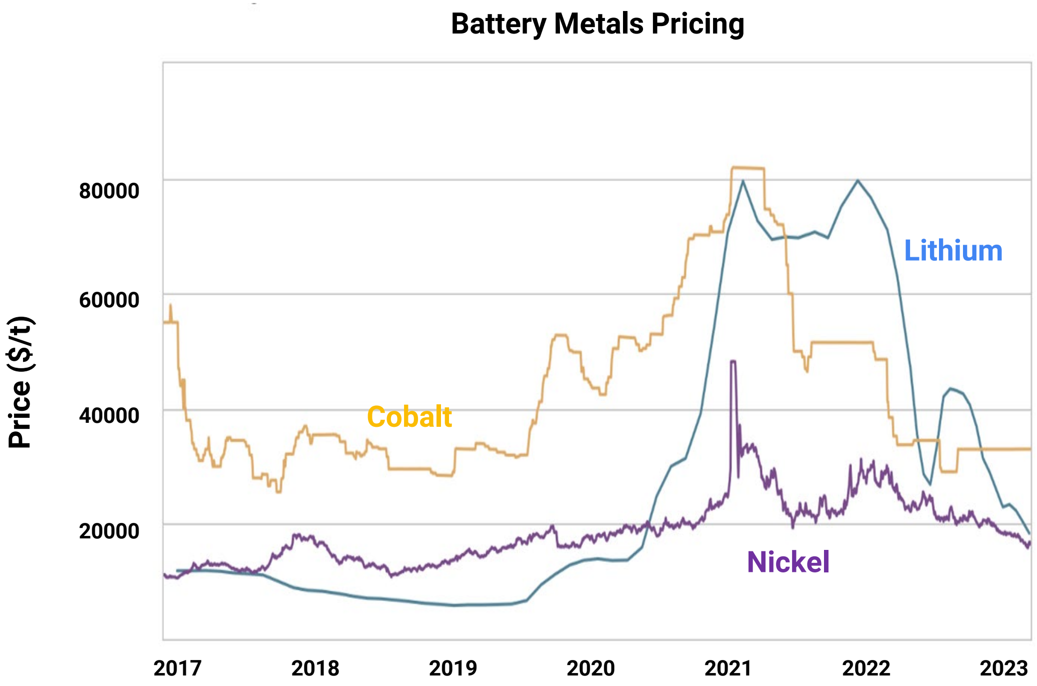
-or-

Why do you care about materials availability?

Practical limits on energy technology scaling may be impacted by materials cost

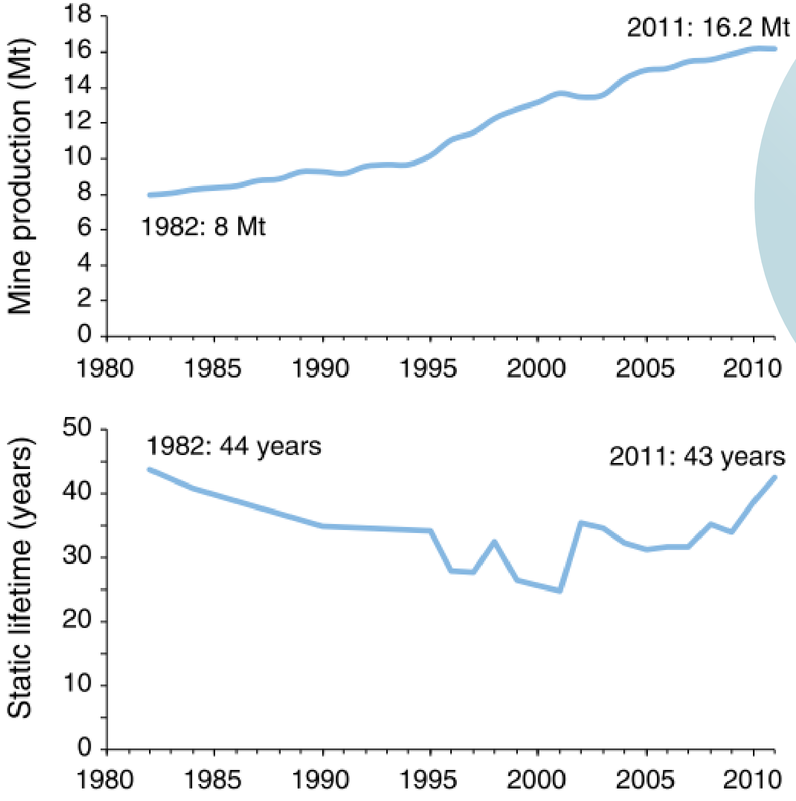


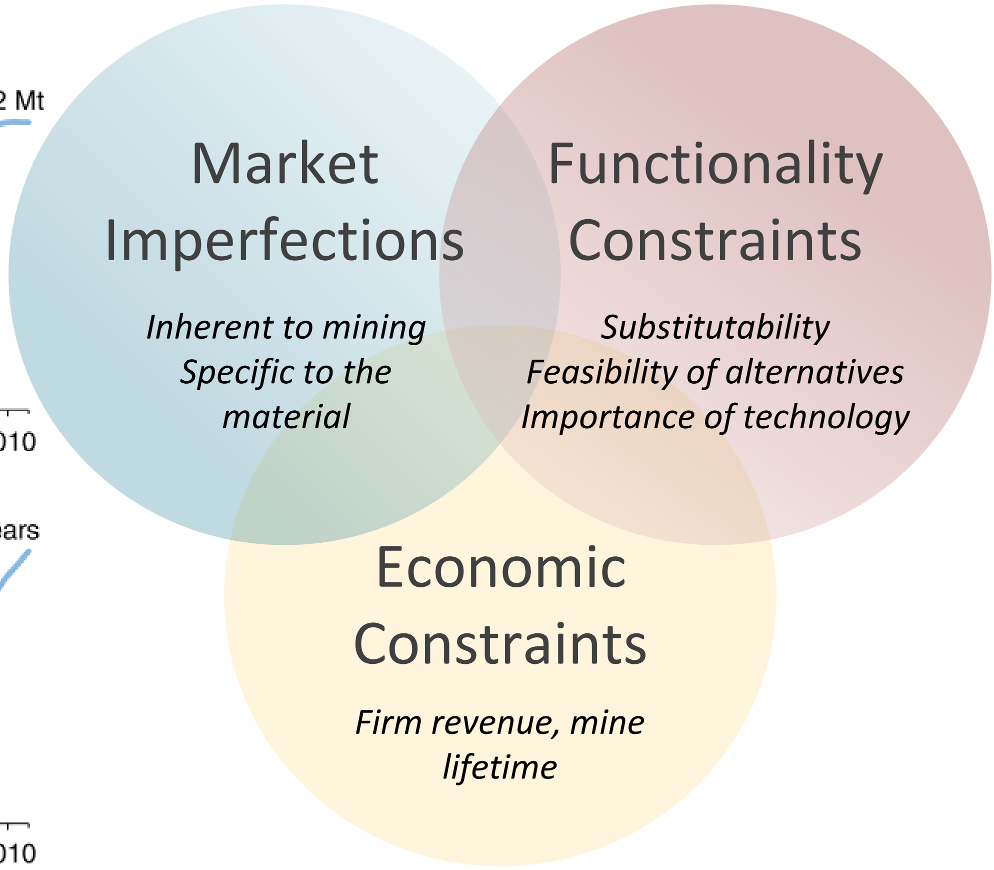




Vaalma, C., Buchholz, D., Weil, M. *et al.* A cost and resource analysis of sodium-ion batteries. *Nat Rev Mater* **3**, 18013 (2018)

Criticality ≠ Scarcity!



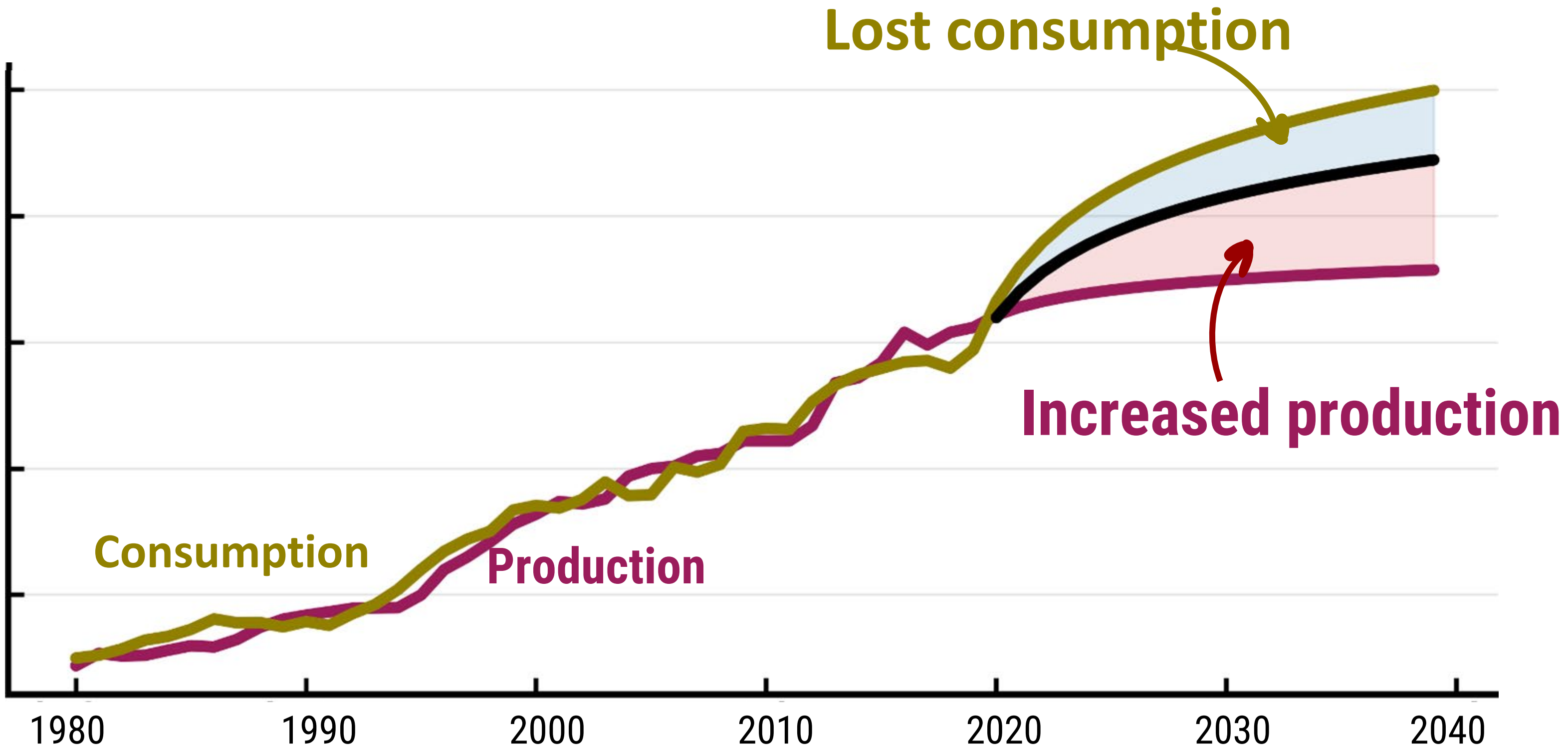


Differences in demand and supply timelines are key- supply cannot ramp-up very fast, demand grew more than expected

Risks: (i) the inability to close the supply-demand gap, and (ii) efforts to close the supply-demand gap

Price is a measure of disruptions and supply risk, availability assessments typically neglect economic feedback

- Price is a function of the production-consumption imbalance
- Consumption responds to price
  - Reduced sales
  - Materials substitution
- Production responds to price:
  - Mine opening, production changes, & closing
  - Resource exploration
  - Recycling

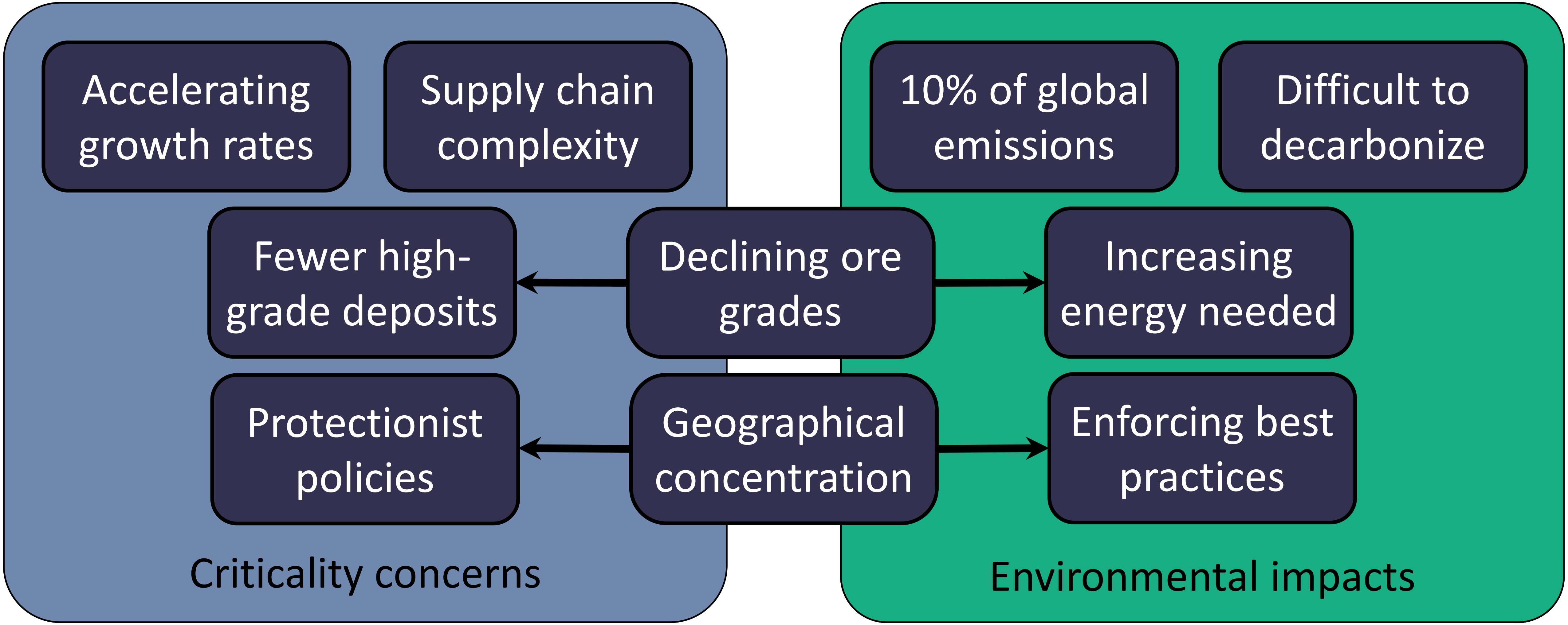


High material costs leads to 28% larger emissions from reduced EV deployment

Wang et al. "China's electric vehicle and climate ambitions jeopardized by surging critical material prices." Nature Communications 14.1 (2023): 1246.

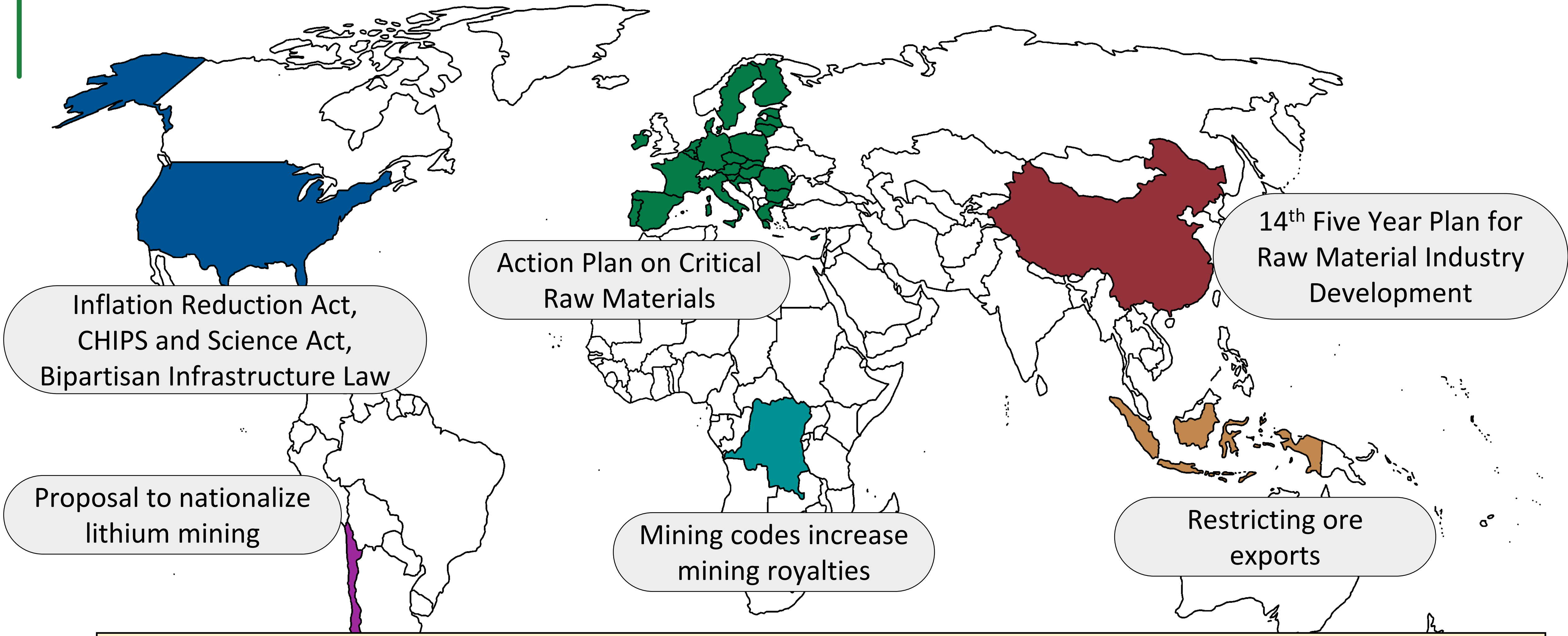
Figure from Ryter (2023), "Mine to Table: Technology and Policy Strategies for Sustainable Mineral Supply Chains in the Low-Carbon Energy Transition

Primary minerals extraction will be an essential element of scaling battery materials and electrification



McNulty et al. *Economic Geology,* 2022.
Watari et al. *Resources, Cons. & Recycling,* 2020.
Jowitt et al. *Comm. Earth & Env.,* 2020.
Azapagic. *Journal of Cleaner Production,* 2004.
Northey et al. *Global Env. Change,* 2017.

These challenges are increasingly recognized by governments



Increasing need to understand how an integrated community can respond

Figure from Ryter (2023), “Mine to Table: Technology and Policy Strategies for Sustainable Mineral Supply Chains in the Low-Carbon Energy Transition

Which material do you think has the highest risk of availability concerns?

Cobalt, Lithium, Nickel, Copper, Graphite

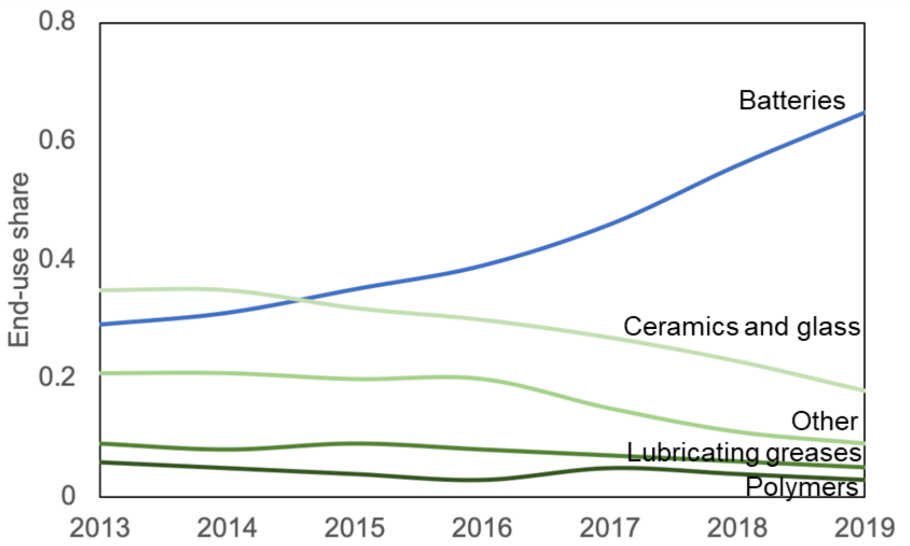
Supply challenges vary by mineral

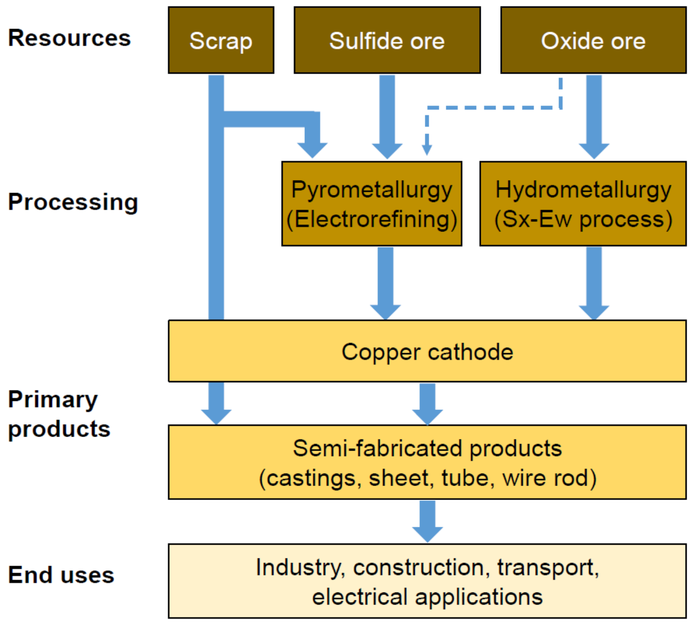
Copper:

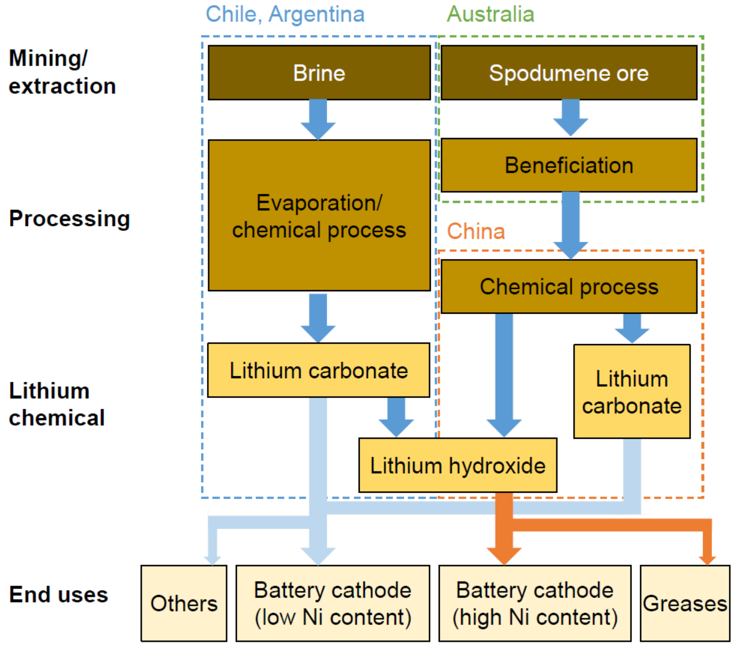
- Challenging to substitute
- Declining ore quality and reserve exhaustion
- Mines in S. America and Australia are water stressed

Lithium:

- Required for most chemistries Production has grown rapidly
- Extracted from diverse and emerging sources
- Chemical production bottleneck depressed prices

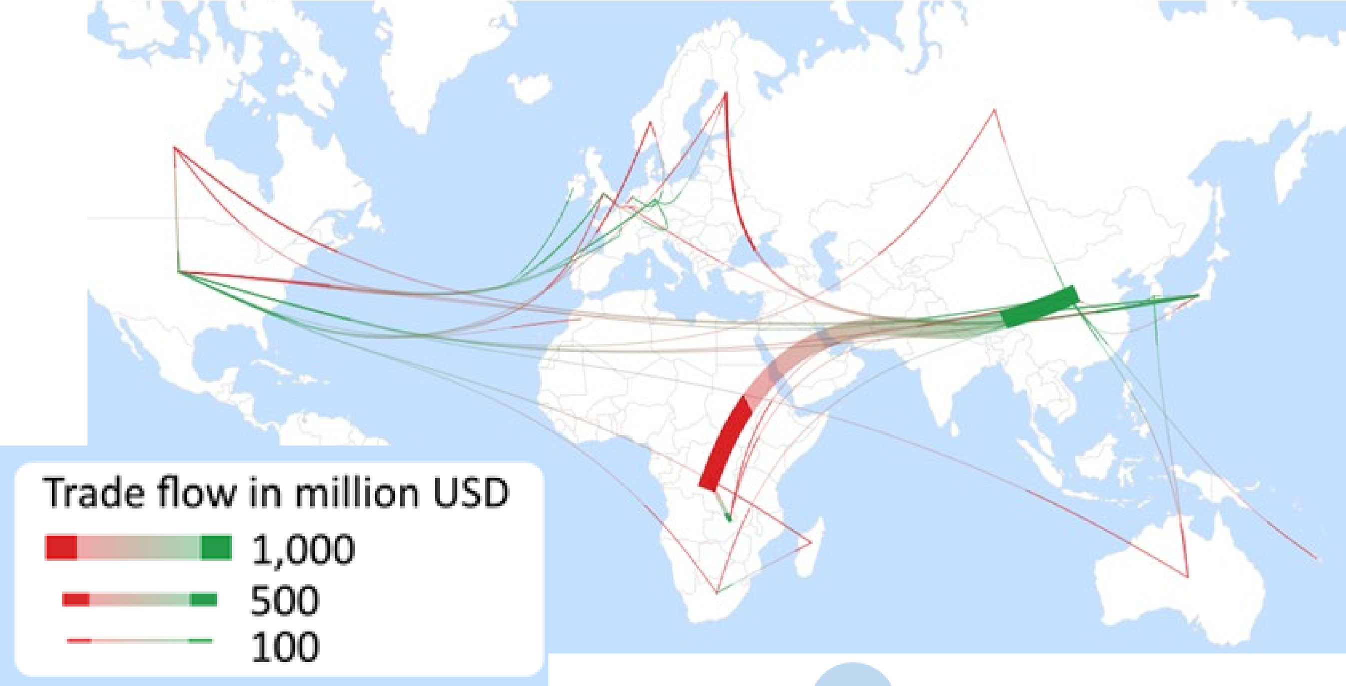


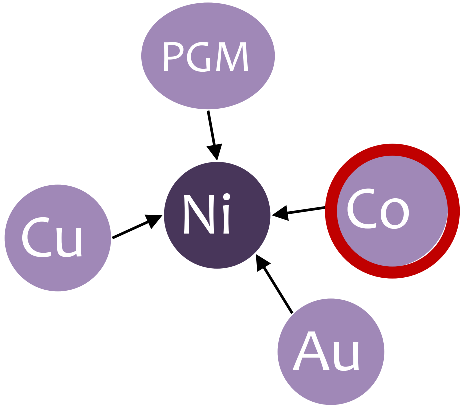


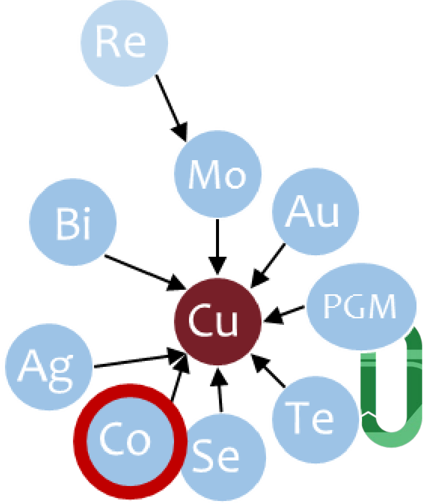


Cobalt: Production and processing are highly concentrated in DRC and China

- Social and political consequences of extraction
- By/coproduct economics (inelastic supply in response to demand)
- Temporal challenge of chemistry shift

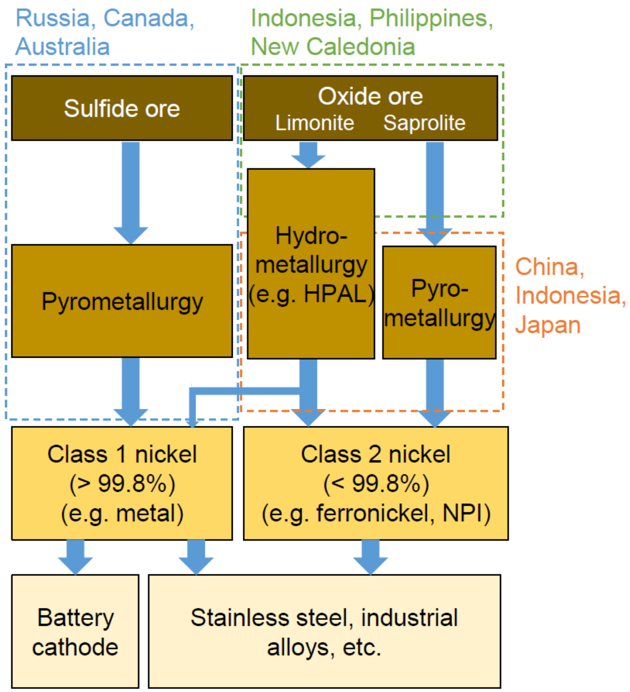


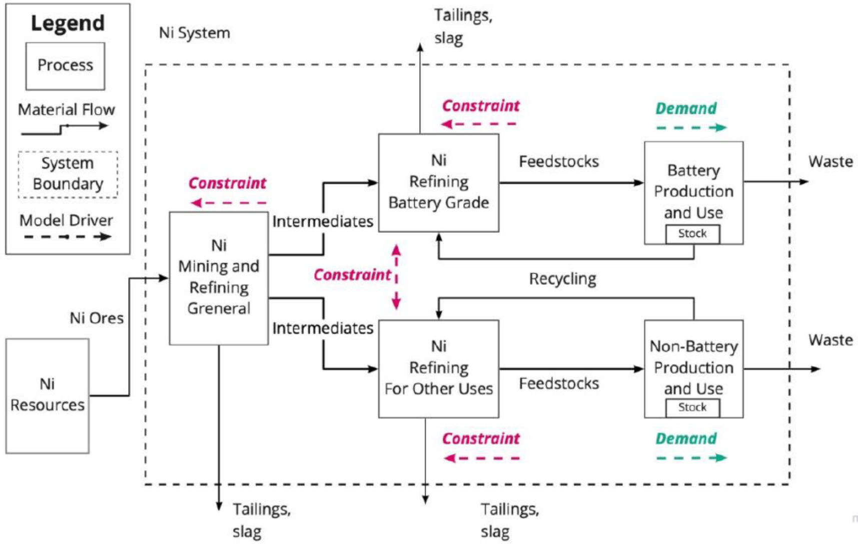




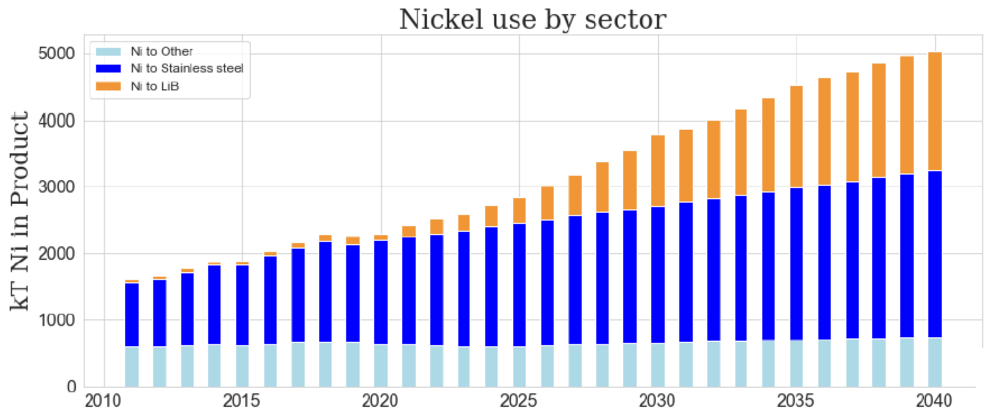
Supply challenges vary by mineral: Nickel

- Majority of the supply is not currently battery relevant; challenging historical CAGR
- Tightening of Class 1 supply; nickel sulfate currently relevant for battery
- Alternatives cost-prohibitive or emissions-intensive



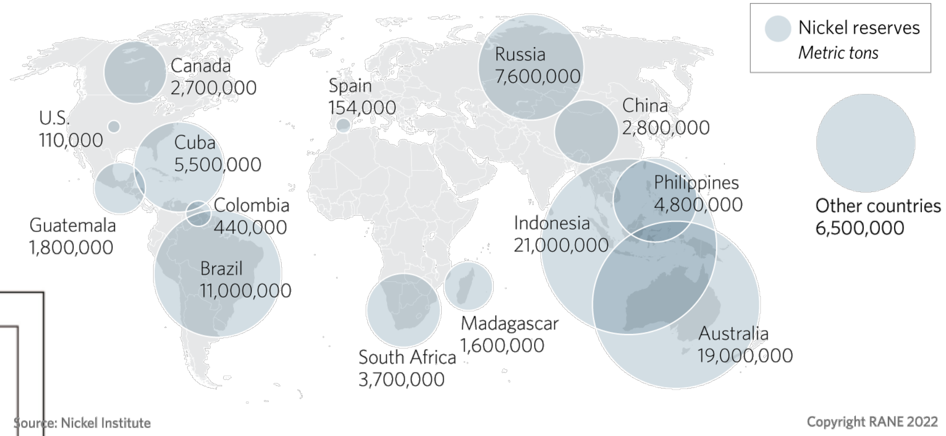


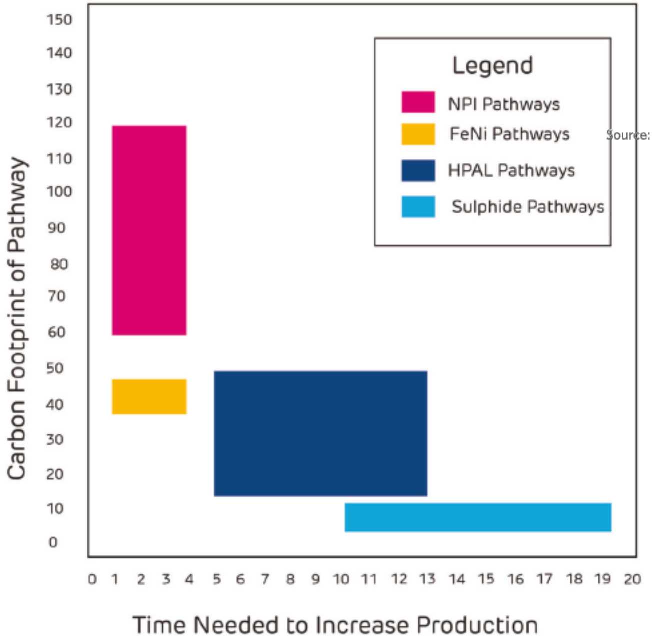
What will the global environmental impact of nickel be in 2050?



Global Nickel Reserves

Nickel is primarily used for stainless steel (69%), with batteries second (13%), followed by alloys (7%), electroplating (5%) and special steels (5% each). Nickel is found in different forms, including nickel sulfide ore (a key component in lithium-ion batteries) and lower-grade lateritic ores, such as limonite and saprolite ores (which are commonly used for creating stainless steel).

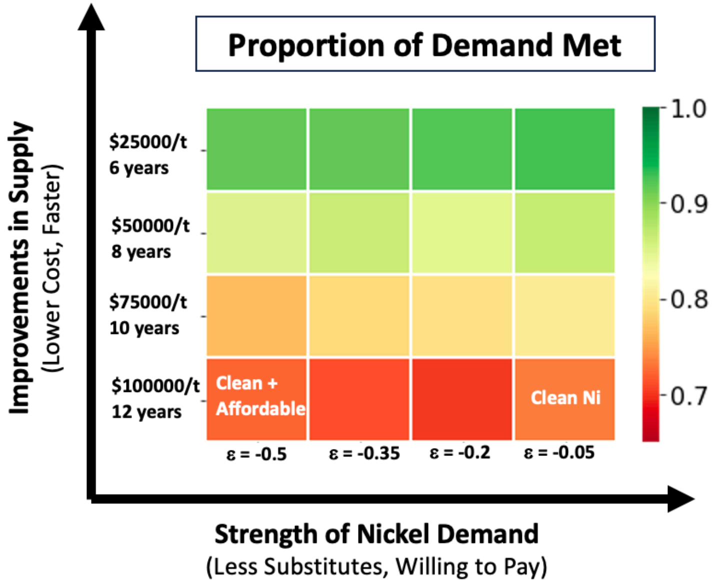


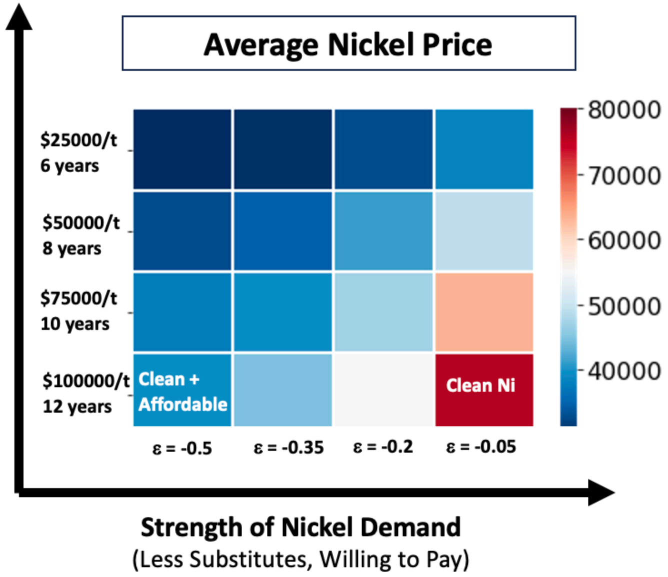


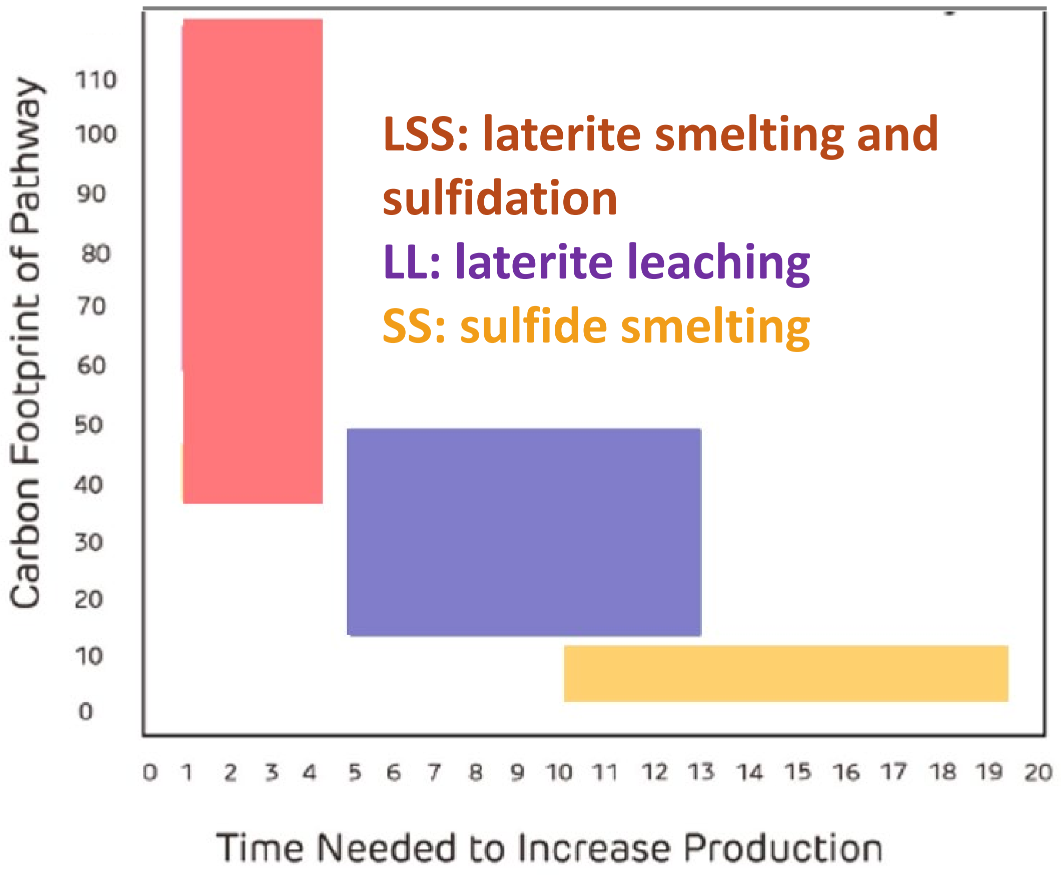
Battery-grade nickel leads to environmental and economic tradeoffs

How can we could be sourcing and processing as sustainably as possible?

How do we prioritize technology investment?

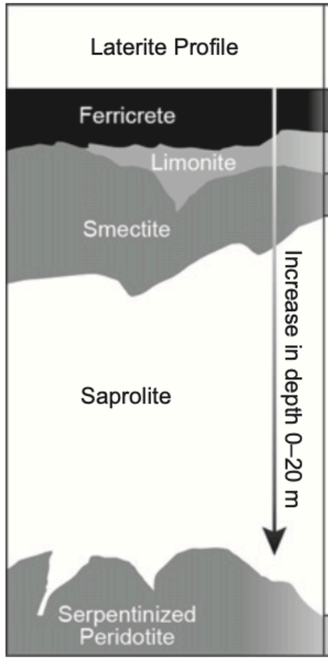






Source: Olivetti group and Materials Systems Lab
Not for citation without permission

A *deeper* look into laterites:
mineralogical realities dictate processing possibilities



Common Name	Minerals	Approximate analysis (%)			
		Fe	Mg0	Ni	Co
Ferricrete	Goethite	>50	<0.5	<0.8	<0.1
Limonite	Hydrated Fe0(0H)	40–50	0.5–5	0.8–1.5	0.1–0.2
Smectite	Nontronite	10–30	5–15	0.6–2	0.02–0.1
Saprolite	Serpertine Talc Sepiolite Nontronite	10–25	15–35	1.5–4	0.02–0.1
Bedrock	Peridotite	5	35–40	0.3	0.01

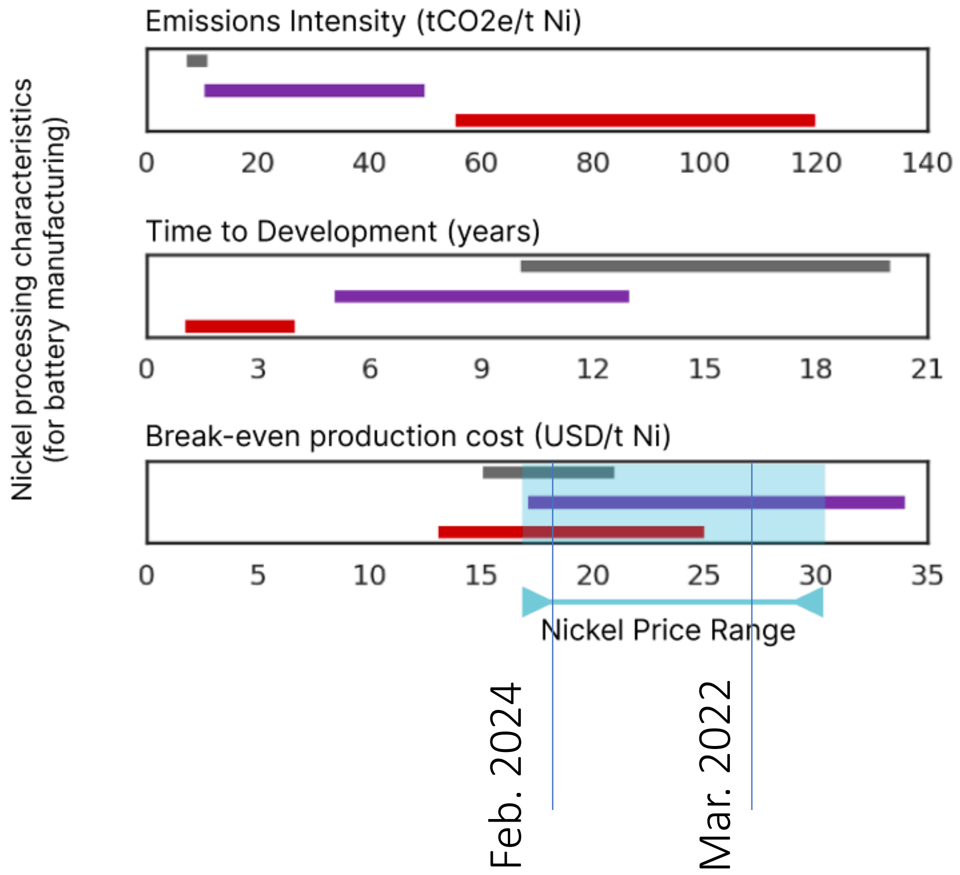
FIGURE 3.1 An idealized profile of a laterite deposit. At the surface, the iron content is high and the MgO content is low. With increasing depth, this position reverses so that at the bottom of the deposit, the MgO content is high and the iron content is low. Ferricrete is a hard layer of soil cemented by iron oxides.

HPAL can produce mixed hydroxide and sulfide product (MHP/MSP) intermediates from limonite minerals.

Smelting can produce ferronickel (20-40% nickel) products from saprolite minerals and nickel pig iron (8-15%) with low grade saprolite and limonite minerals.

Figure from Crundwell (2011)

Different processing pathways manifest different economic (capex, opex), environmental and timeline considerations



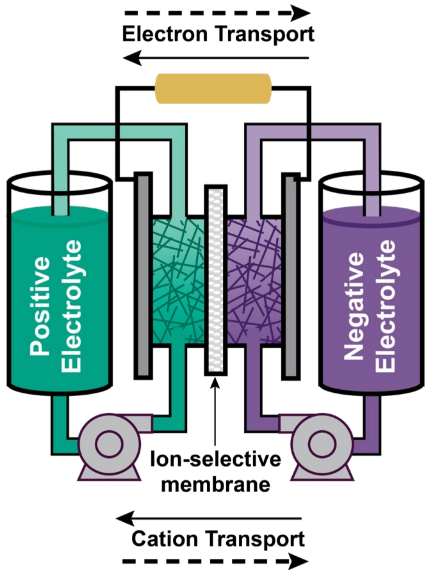
- FeNi/NPI to matte conversion is energy intensive and in regions of coal based electricity, carbon intensity can be very high.
- Sulfide projects take a long time due to environmental and permitting requirements, HPAL additionally has operational scale-up issues as well.
- Longer time as well as high upfront capital investment needed for HPAL capacity makes it expensive.

Sulfide – Matte – Class1/NiSO4 (Pyrometallurgical) - 1

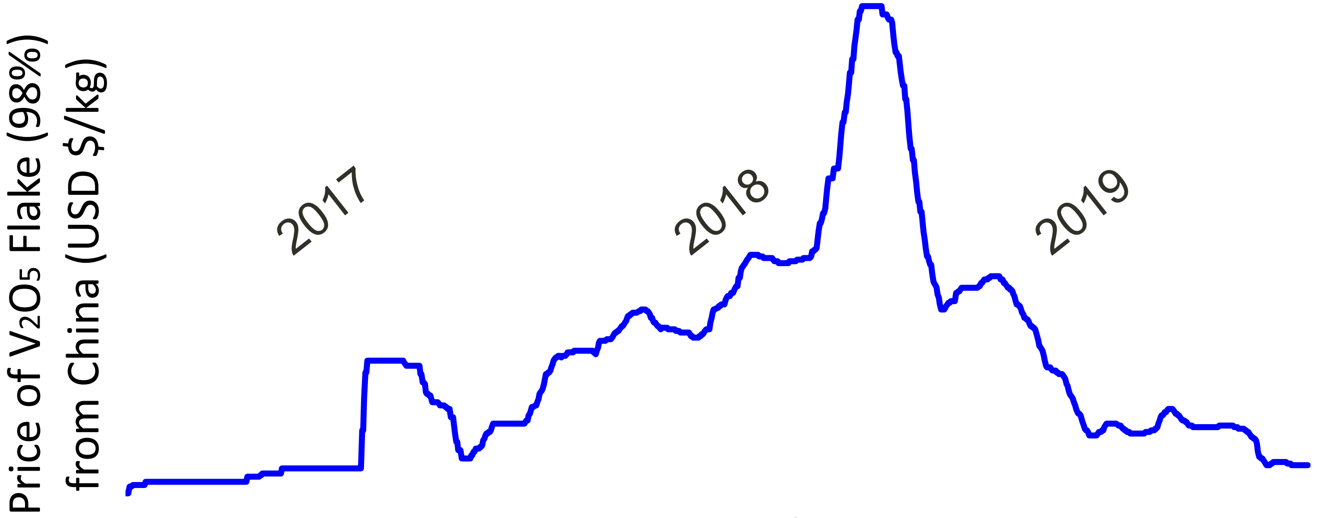
Laterite – MHP/MSP – NiSO4 (**HPAL**, Hydrometallurical) - 2

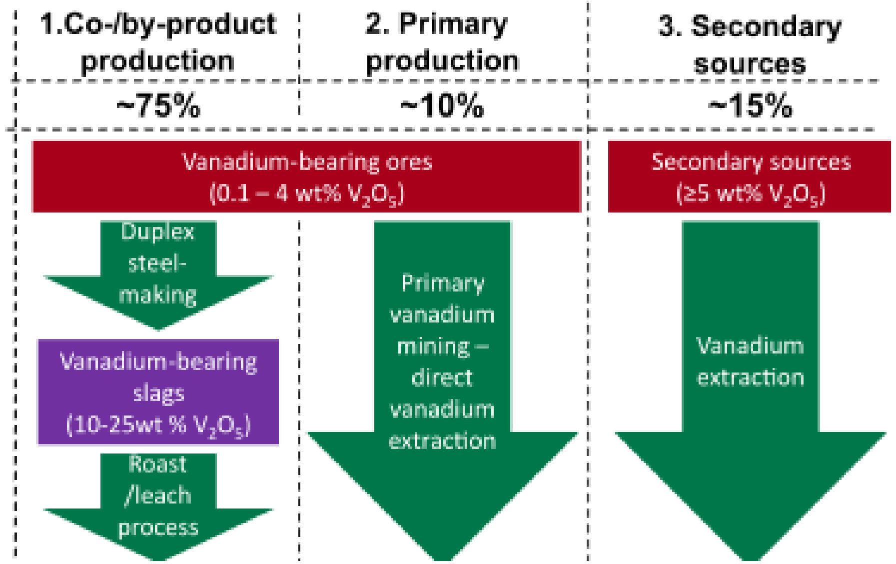
Laterite – FeNi/NPI – Matte – NiSO4 (**Smelting**, Pyrometallurgical) - 3

Vanadium used primarily in steel could be used for flow batteries, additional sources would come from byproducts



Redox flow batteries





Source: Rodby & Brushett

- 85% of world's vanadium from South Africa, China and Russia.
- 65% made in 10 mills as a by-product of steel
- Alternatives are diffuse with poor economics

Industrial Strategy to include market feedbacks and provide supply *and* demand support, where *necessary*

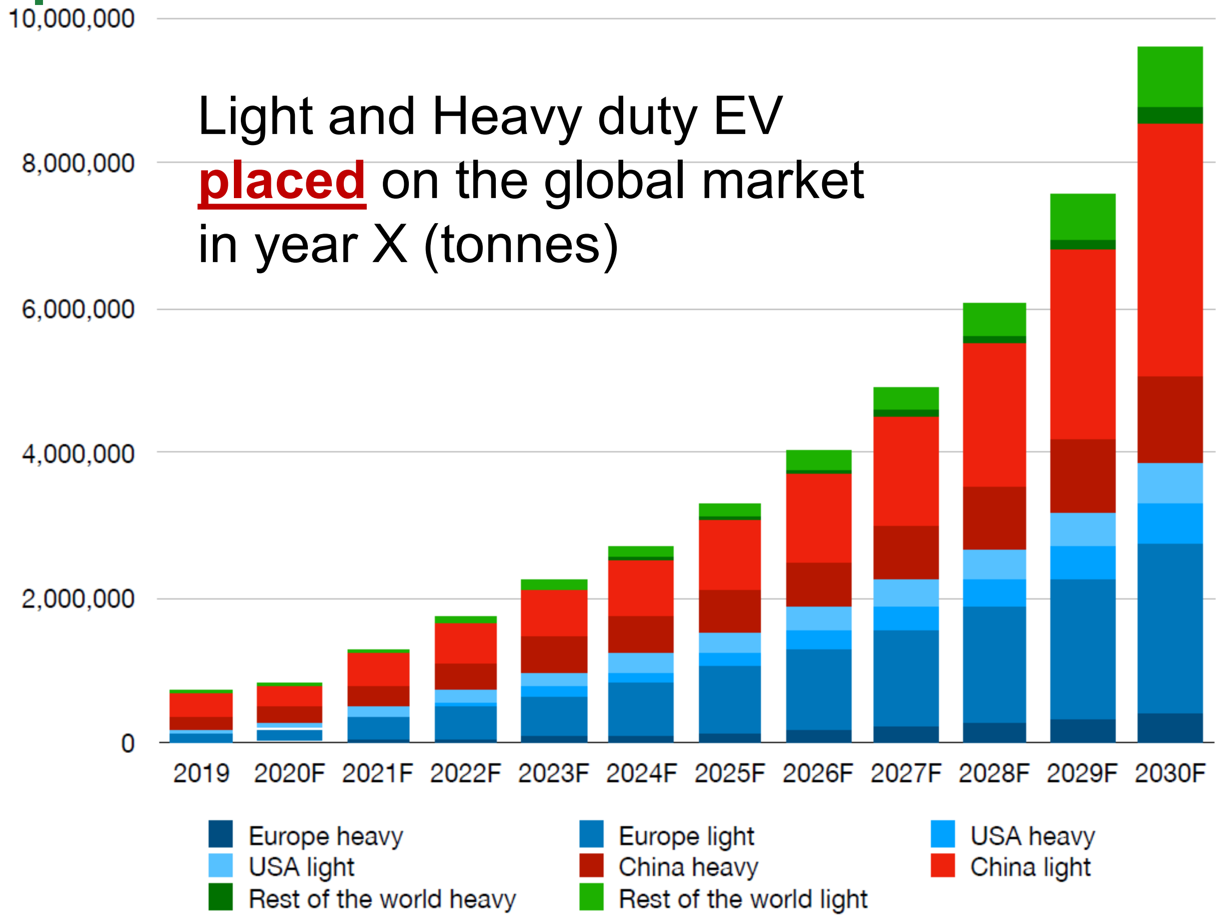
Reducing supply development timelines requires coordination between policymakers, investors, mining companies and consumers

- Lowering financial risks for mining companies can help speed up decisions
- Off-take agreements can reduce uncertainty in price and demand
- Streamlining permitting and early-stage community engagement can reduce delays
- Newer technologies such as direct lithium extraction can reduce processing times

Policies and technology innovation can help _strengthen demand_

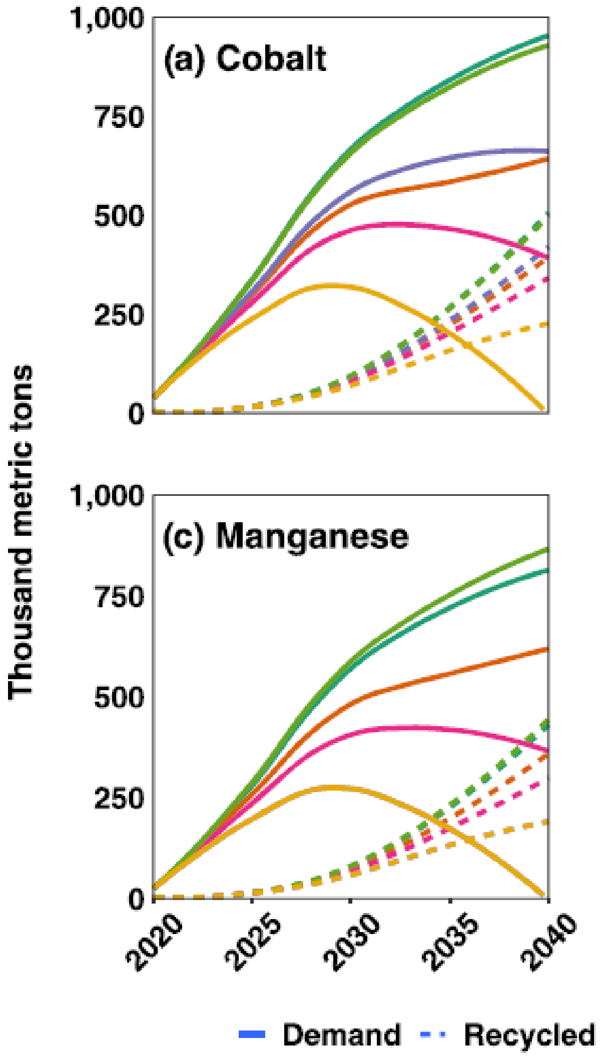
- Subsidies for electrification increases demand and reduces elasticity
- Development of alternative battery chemistries and lowering material intensities can ensure that less material consumption is needed to meet clean energy target

Over the next decade, managing end-of-life batteries through recycling will become a requirement, 33% annual growth rate in battery demand

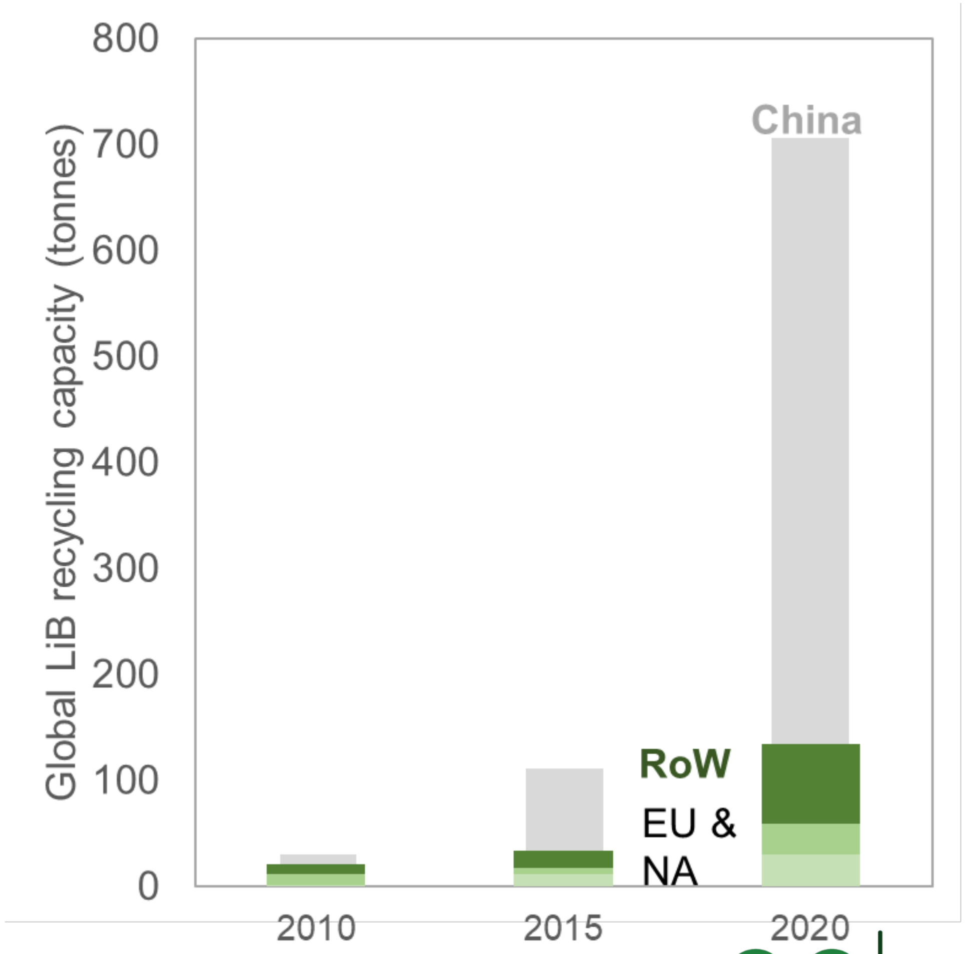


Source: Circular energy storage

Recycling will not contribute significantly to meeting material supply now for exponentially growing deployment trajectory

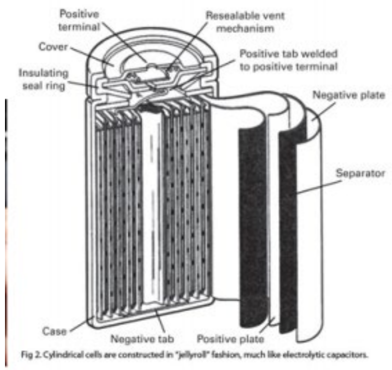


Curves show different demand scenarios



Source: Dunn, et al. ES&T
https://doi.org/10.1021/acs.est.0c07030

Li-ion battery pack is a complex system:
the variety of materials and design hinders recycling



(b) Anatomy of Cylindrical Cell

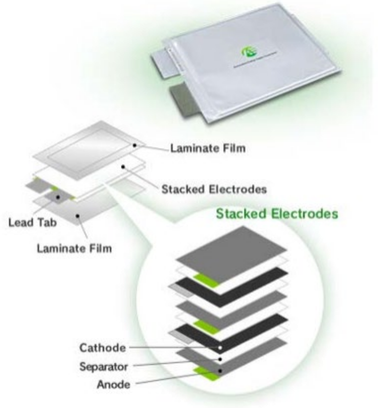
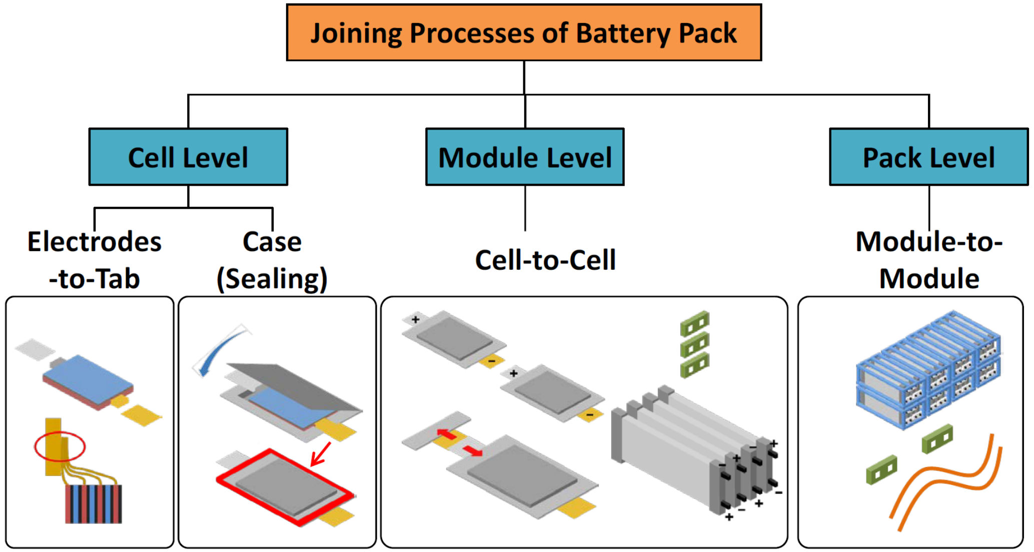
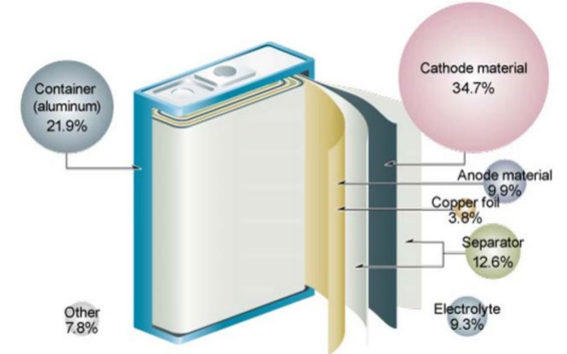


FIGURE 1.4 SCHEMATICS OF POUCH TYPE CELLS

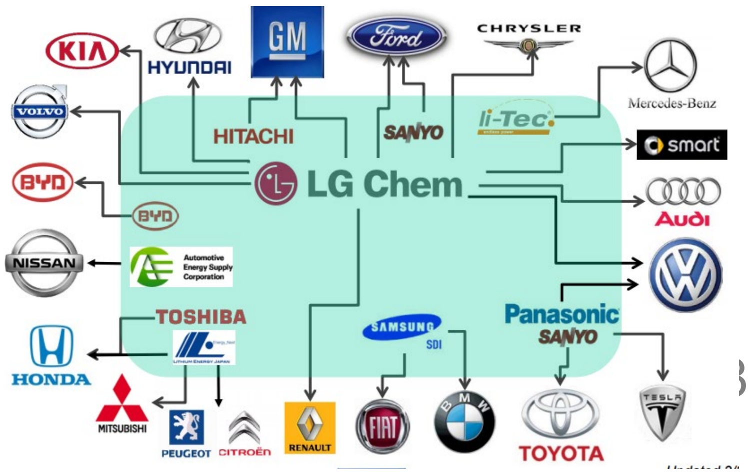




IRE 1.3 AN ANATOMY OF A PRISMATIC LI-ION BATTERY CELL, WHERE THE % INDICATING THE ESTIMATE COST

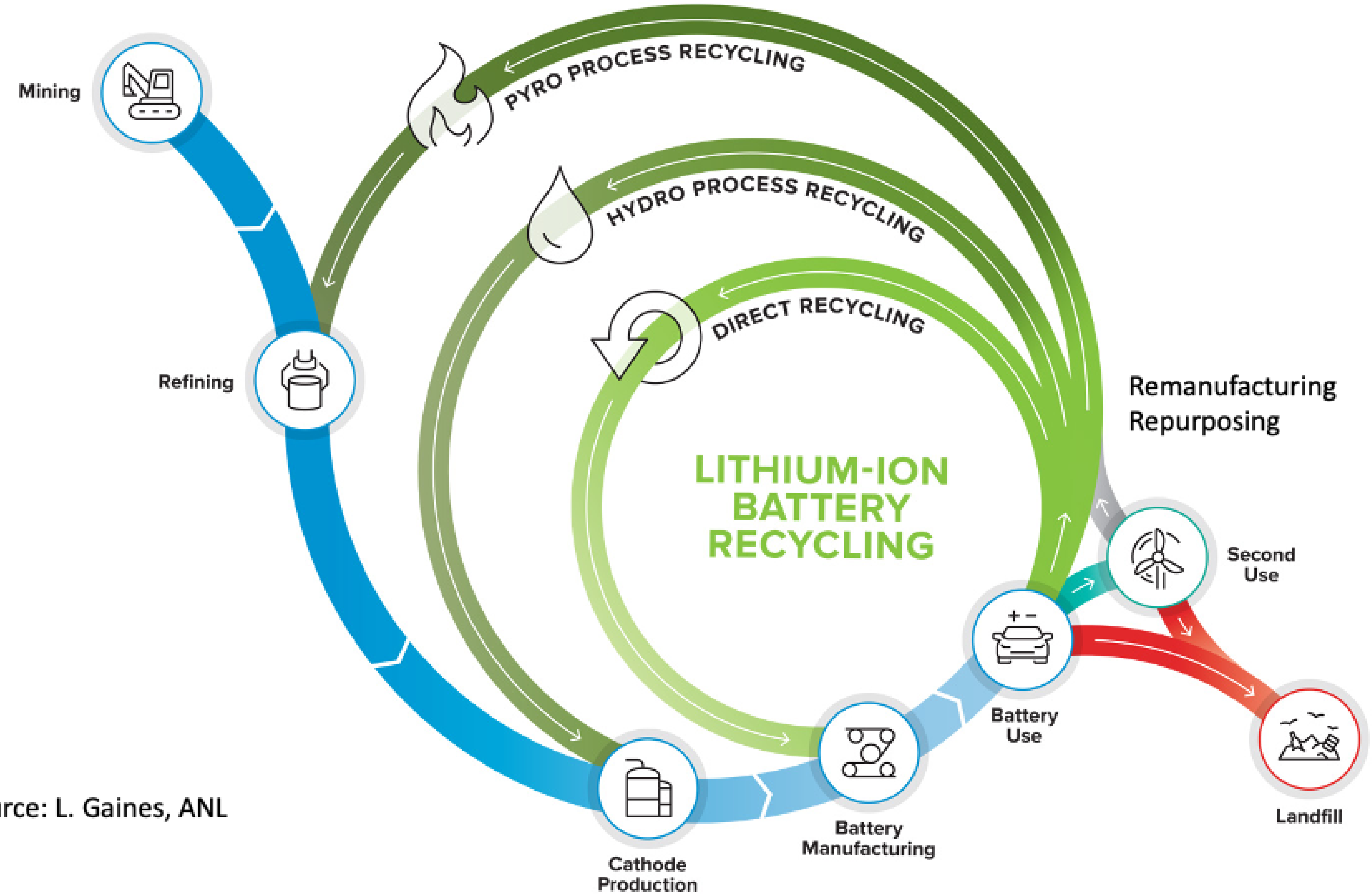
No standard or labeling for battery cells, modules or packs

Fixtures, fastenings, screws, bolts, adhesives, sealants and solders



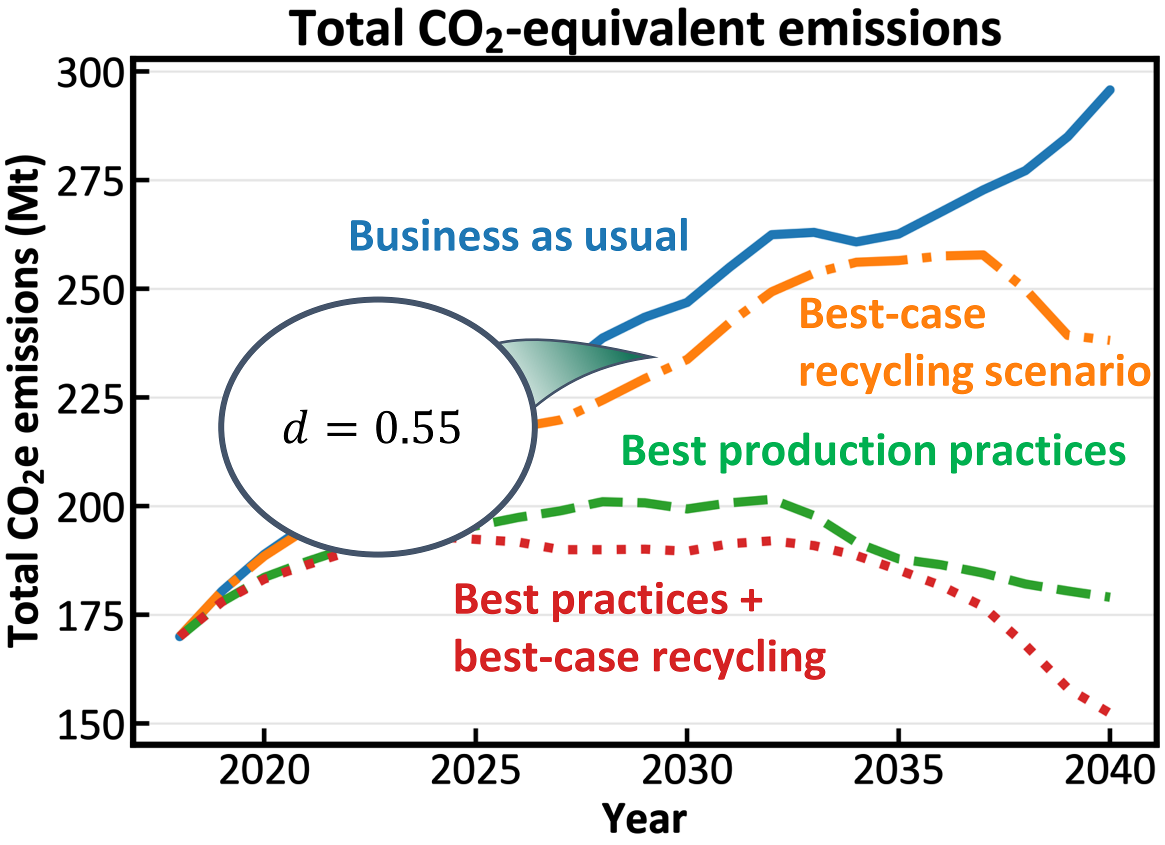
Harper, G. *et al. Nature* **575**, 75–86 (2019).

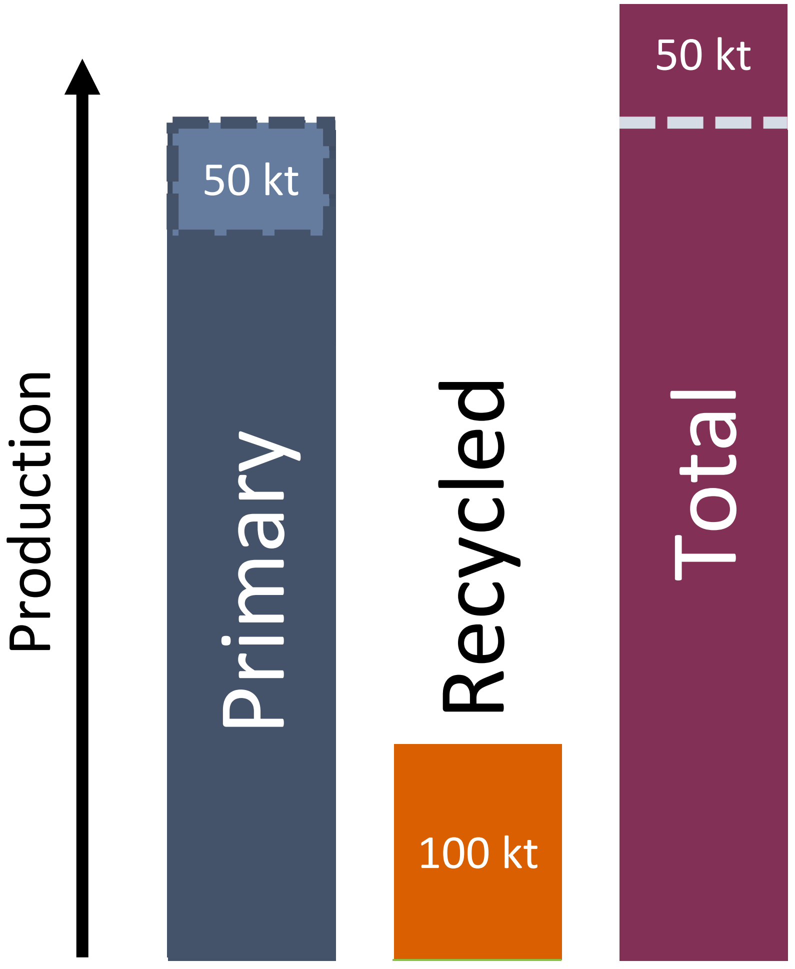
There are economic and environmental tradeoffs based on different recycling technologies



Source: L. Gaines, ANL

How can we prioritize investment by industry to meet necessary climate targets?



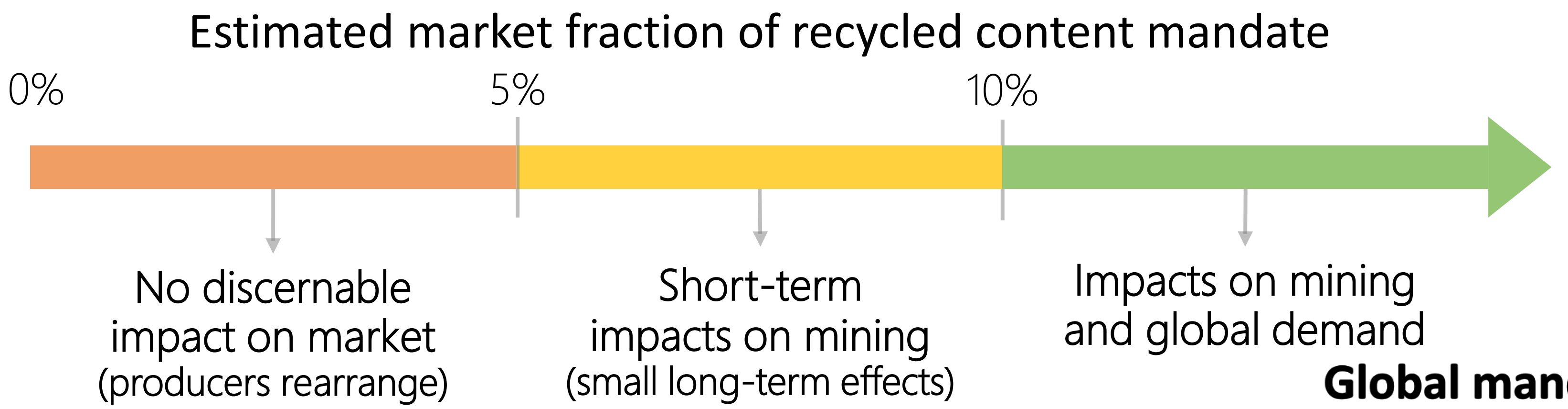


Partial Displacement ($d = 0.5$)

$$d = \frac{\text{Decrease in primary production}}{\text{Increase in recycled production}}$$

Ryter et al. *J. Ind. Ecol.* (2022)

Impact of recycled content mandates depends on market share

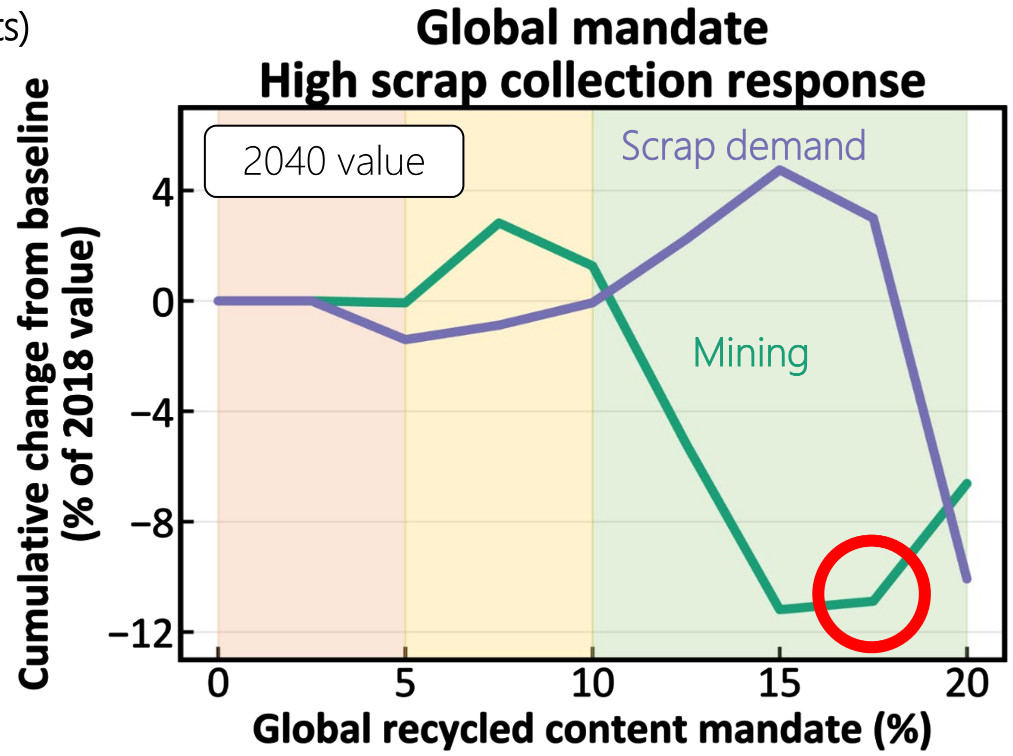


When more than 10% of market impacted by recycled content mandate:

- Substantial mining reductions
- Up to 12% increase in cathode and scrap prices

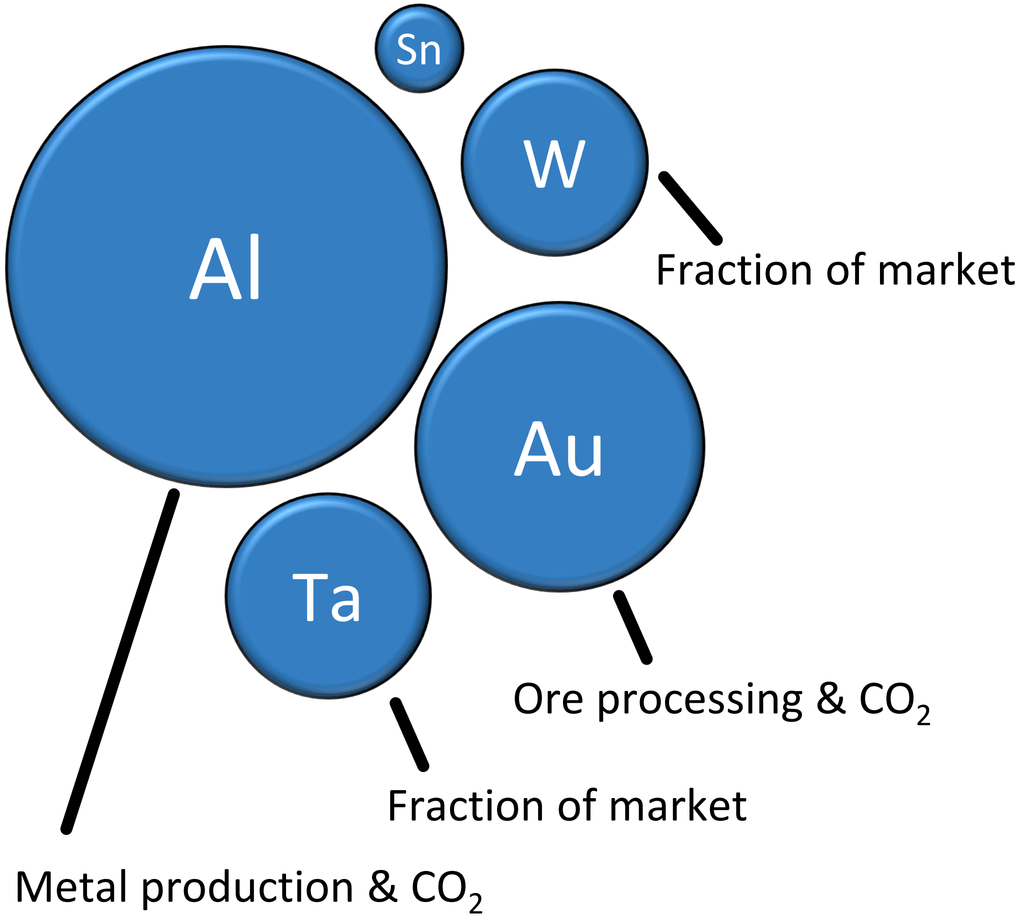
Mining reductions are tied to increasing scrap collection

If collection is insufficient, prices rise and demand falls

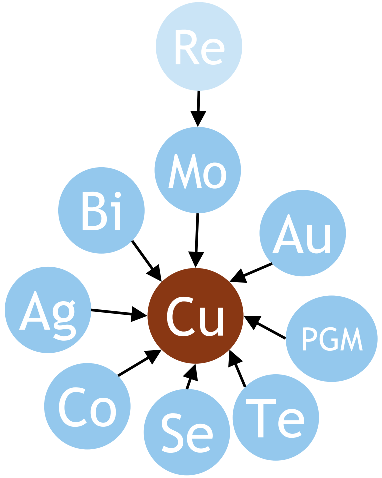


When can industry have relevant impacts through recycling?

Diameter ∝ normalized sum of all mining & CO_2 changes



Average lead times for mining projects = 18 years



Global trends in use of aluminum in transportation lead to ~10% unusable scrap

China banned low-grade scrap imports in 2018 to reduce local pollution

- Led to redistribution of scrap processing throughout Asia
- Early 2019 announced a higher-grade ban, currently require >99.1% Cu

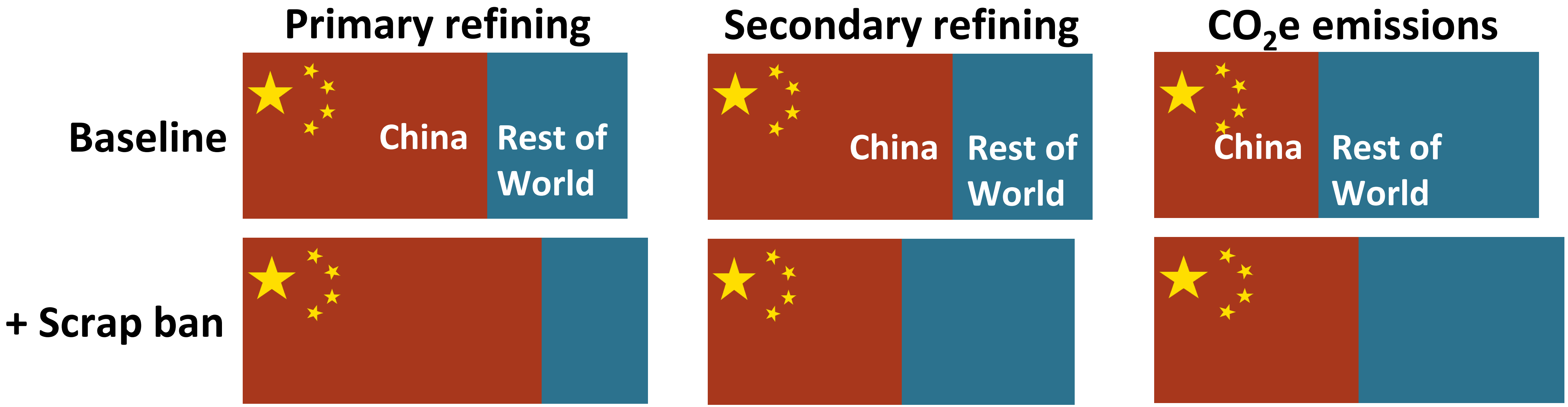
Change in scrap imports 2017-18 (t Cu):

Imports to China: +100,000; +10,000; 0; -10,000; -100,000

All nations: +5,000; -5,000

Ryter et al. *Nat. Comm.* (2021)

Emissions increase both in China and globally

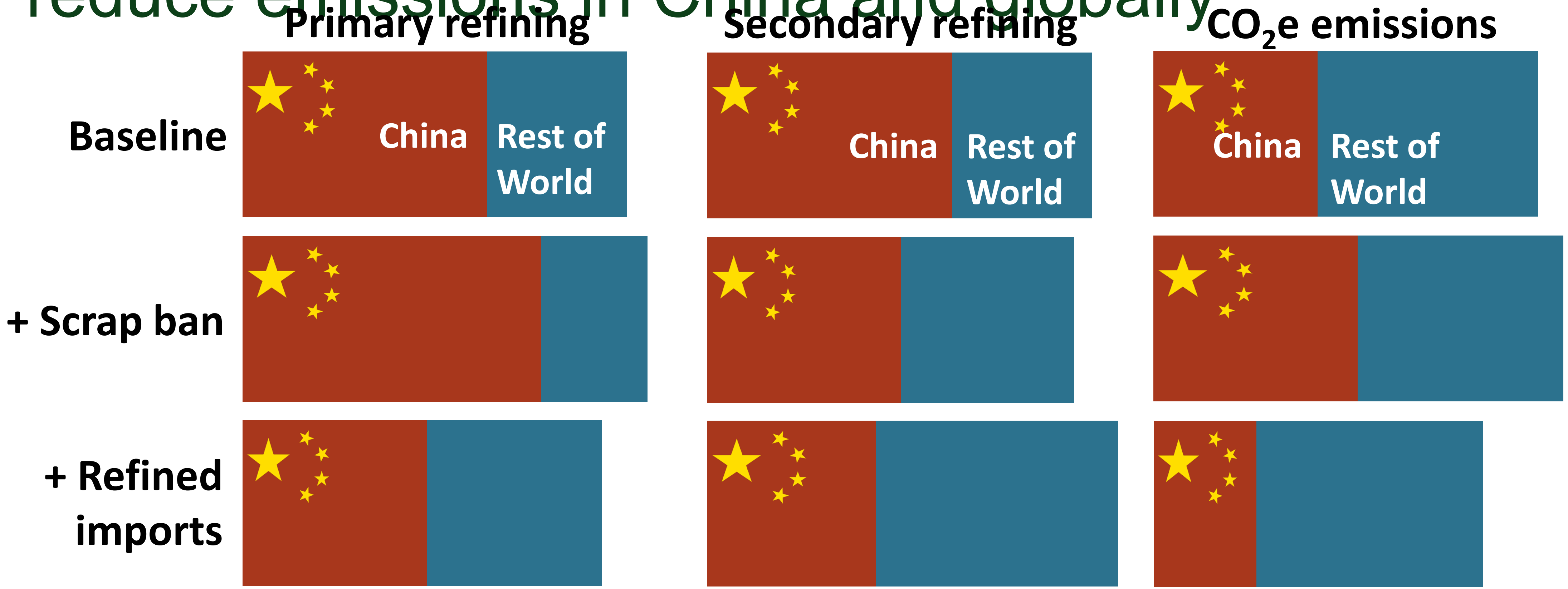


- **China**: scrap shortage increases scrap prices, shifting refineries toward primary material
- **Rest of world**: Scrap surplus eventually increases scrap use
- **Globally**: small change in mining, refining, and scrap use, but emissions rise

Ryter et al.
Nat. Comm.
(2021)

1. **Primary refining emissions are larger than scrap refining**
2. **China's primary refining has higher emissions than RoW**

If China's ***refined copper imports*** also increase, we reduce emissions in China and globally



- **China**: Increasing refined metal imports reduces total refining
- **RoW**: Increased demand for refined metal enables faster secondary ramp up
- **Globally:** Increased RoW emissions are more than offset by China reductions

Global and local emissions reductions are possible by importing higher on the value chain, creates more than simple redistribution

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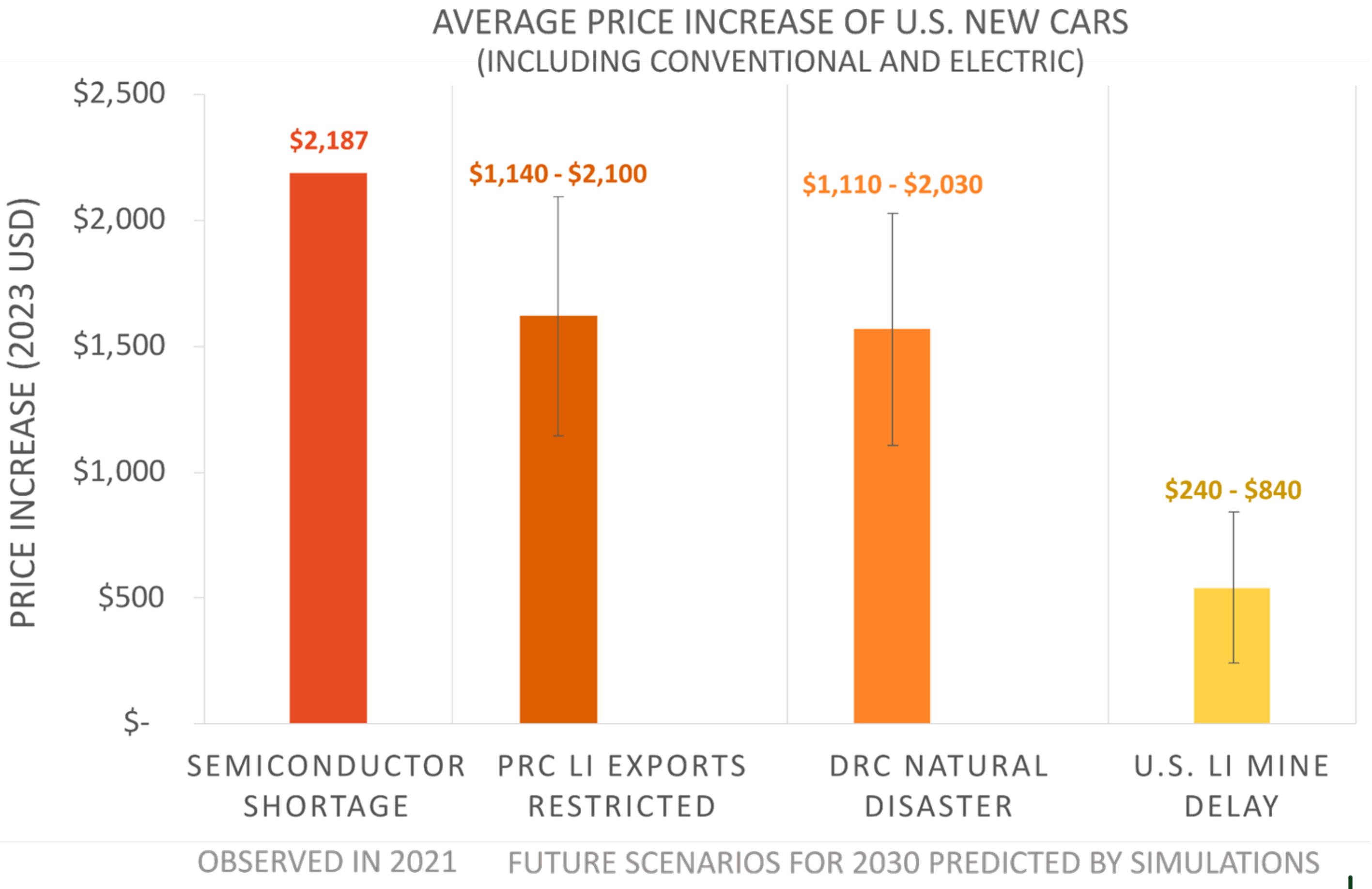
Critical mineral supply shock scenarios

Scenario		Quantity	Estimated resulting median material price (2023 USD)	Estimated NMC811 battery production cost (2023 USD)
Lithium		2.8 Mt	$20,000/t LCE	$99/kWh
	PRC lithium export *restriction* causes 15% refined supply reduction	2.58 Mt	$80,000/t LCE	$126/kWh
	US lithium mine *delay* causes 250 kt raw lithium supply shortage	2.7 Mt	$40,000/t LCE	$108/kWh
Nickel*		3.2 Mt	$20,000/t	$99/kWh
	Declining ore grades cause 800 kt raw supply *reduction*	2.4 Mt	$88,457/t	$138/kWh
Cobalt		302 kt	$49,280/t	$99/kWh
	Human rights abuses cause 14% raw cobalt supply *reduction* to US	274 kt	$199,360/t	$110/kWh
	Natural disasters in the DRC cause 65 kt global raw cobalt supply *reduction*	258 kt	$479,360/t	$126/kWh

Simulations of 2030 scenarios show that lithium and cobalt supply shocks due to geopolitical disputes or natural disasters could impact auto market, similar in magnitude to the recent semiconductor shortage.

Impacts include:

- Price increases of new vehicles (both conventional and electric),
- Nearly 1 million US households unable to purchase a new vehicle,
- $24B of consumer surplus losses,
- Lost wages for battery cell and pack production workers.



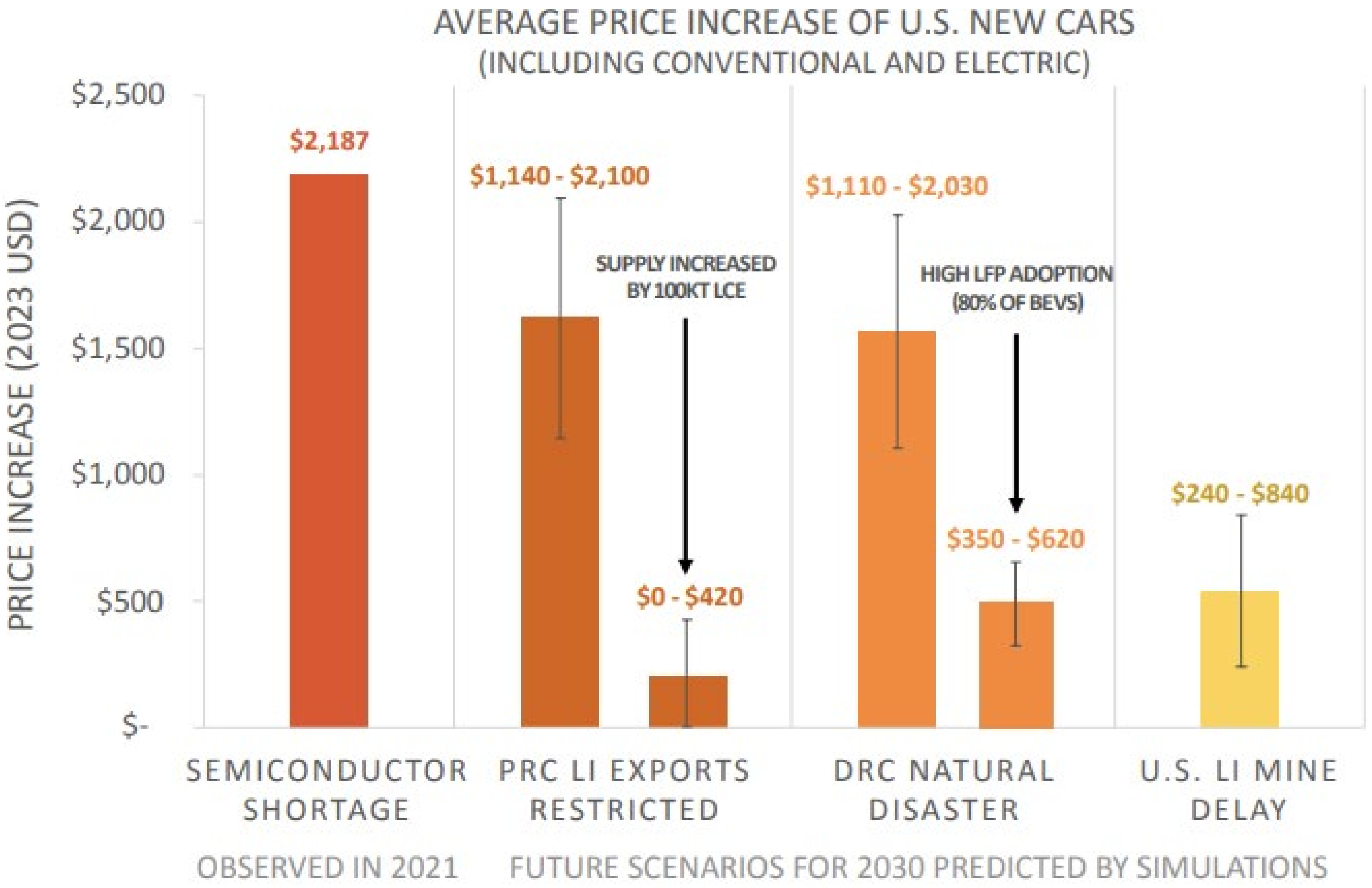
Securing America's Future: A Framework for Critical Technology Assessment.

In collaboration with Kate Whitefoot, CMU

Vulnerabilities to lithium and cobalt supply shocks can be reduced

Actions include:

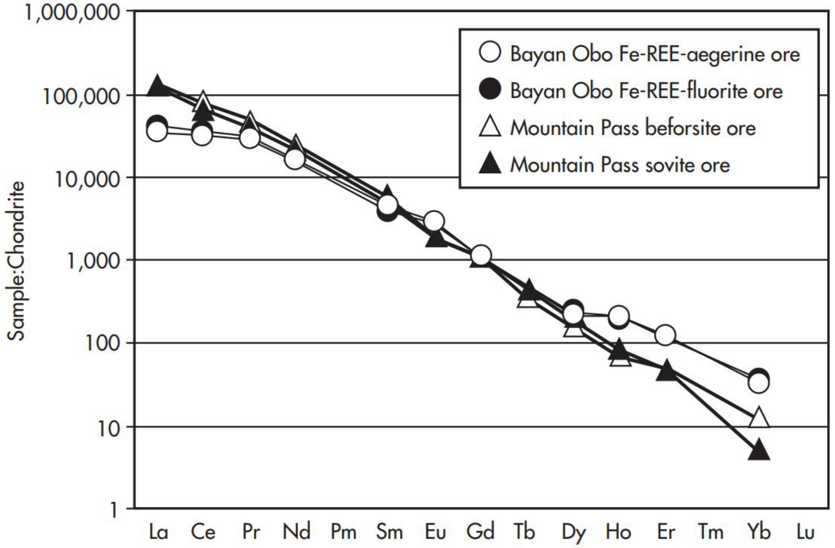
- Encouraging additional supply of lithium domestically or in locations with low risk of trade restrictions
- Increasing use of cobalt-free batteries (such as lithium-iron-phosphate) in the large majority of electric vehicles



Securing America's Future: A Framework for Critical Technology Assessment.

Will demand for certain REEs (Nd, Dy) drive over-production of other REEs? What are the environmental impacts of ‘linked’ REE production?

Distribution of elements in ore

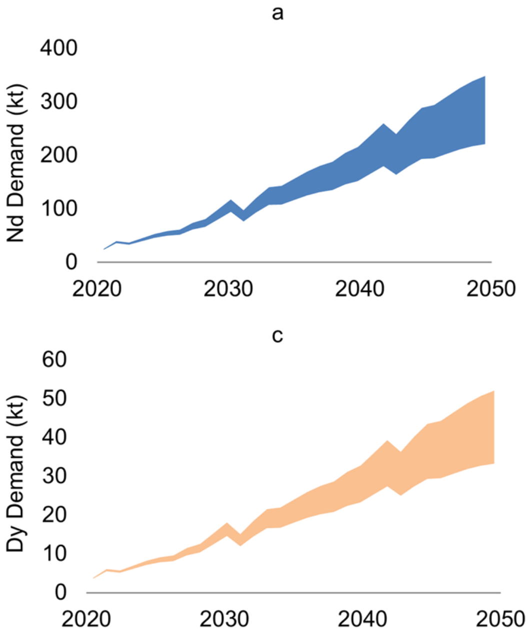


NOTE: REE data not normalized to 100% prior to chondrite normalization.

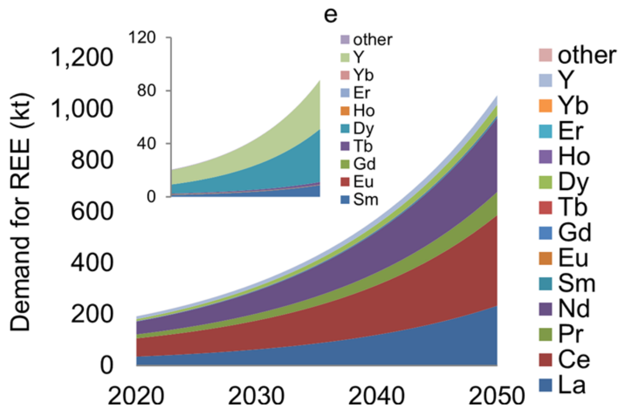
Figure 4. Chondrite-normalized plot of REEs in ores from Bayan Obo, China, and Mountain Pass, United States (data sources: Castor 1986; Yuan et al. 1992)

Castor and Hedrick (2006) Rare Earth Elements

Demand for key elements



Demand for other elements in ore? Balance problem?



Elshkaki (2021) Sustainability of emerging energy and transportation technologies is impacted by coexistence of minerals in nature

Risk within Materials Supply Chains for Transportation 3/15/2024

Speaker: Elsa Olivetti, MIT
Annotated By: Vir Chachra

Summary

The use of renewable energy technologies within the mobility infrastructure is linked to increased demand for materials. Meeting this demand must be grounded in environmental, social and economic development of mineral supply. To support industrial strategy, policy, and technology innovation that meets this objective, we need robust approaches for evaluating the availability of materials, specifically incorporating economic feedback and a structural understanding of how material supply may evolves. This presentation will describe how analytical work can be used to evaluate the impact of factors such as the rate of demand growth, materials substitutability, resource quality, and recycling rates on availability in the long term through cases in copper, lithium, and nickel. The presentation content will cover nuances in battery supply chains and the geographies involved, but also offer thoughts on strategies that reduce the risk of materials supply constraints coupled to regulations that could support increased metal supply while considering environmental and social impacts.

Part I. Literature (for further reading)

1. Jagani, Sandeep, Erika Marsillac, and Paul Hong. 2024. "The Electric Vehicle Supply Chain Ecosystem: Changing Roles of Automotive Suppliers" *Sustainability* 16, no. 4: 1570. https://doi.org/10.3390/su16041570

2. Center for Economic Performance. "The supply chain for electric car batteries is changing the world's geopolitics"Centre for Economic Performance. Accessed March 25, 2024. https://cep.lse.ac.uk/_NEW/publications/abstract.asp?index=10257

3. Jones, B., V. Nguyen-Tien, and R. J. R. Elliott. "The Electric Vehicle Revolution: Critical Material Supply Chains, Trade and Development." The World Economy 00, no. 00 (2023): 1–16. https://doi.org/10.1111/twec.13345.

Part II. Recent News

1. "Biden's EV Vision Hits Supply Chain Snags with Sourcing Batteries." Bloomberg. Accessed February 21, 2024. https://www.bloomberg.com/news/newsletters/2024-02-21/biden-s-ev-vision-hits-supply-chain-snags-with-sourcing-batteries?embedded-checkout=true.

2. "DOE Plans $710M in Loans to Boost EV Supply Chain," E&E News, accessed [Insert Access Date], https://www.eenews.net/articles/doe-plans-710m-in-loans-to-boost-ev-supply-chain/.

Part III.

<u>Moderator questions</u>

What materials are specifically difficult to extract and have significant challenges?

- Cobalt has issues, a lot of it comes from DRC and is processed in China
- Mines are built for nickel and cobalt is a byproduct, this effects its supply elasticity
- Lithium: Required for most battery chemistry. Energy intensive to process. Chemical processing challenges are downstream
- Materials are not monoliths

Why is recycling materials so complicated? What are the implications around it?

- Volume of materials coming back are very small
- Recycling is challenging giving the pace we are electrifying at
- Need to build the infrastructure to do recycling
- Capacity is being built in China
- Complexity
- Investments in different sectors of the supply chain effect how recycling happens
- There is direct recycling, chemical recycling, thermal recycling and all those have different footprints.

What is a battery passport?

- Battery passports give us a data tracking system for batteries and can be helpful in thinking and tracking about usage

<u>Audience</u>

How do semi-conductors factor into this conversation?

- Silicon comes up as a material but it is complex

What is the industrial strategy needed to transition to renewables?

- Industries need to look at supply and demand at the same time and adapt to both
- Nickle in Indonesia is an example, where coal fired processing is creating environmental and economic impacts
- Indonesia is outcompeting outside the country which is making the processing environmentally detrimental in total

How much opportunity is there to make this extraction less carbon intensive?

- There are opportunities throughout the industry and processing supply chains

Should we rethink EV transition due to these issues?

- No, we have to decarbonize in every way and manage the implications of mining and challenges

How do we not create other problems by solving climate change?

- Sustainable supply chains need to be defined and we need policy innovations so we avoid externalities

Part IV. Summary of Memos

Themes from Other Memos

- As battery systems and EV's become more durable, recycling these materials becomes more difficult
- There are externalities of the EV transition due to increased dependence of finite materials like complex geopolitics and complex/costly supply chains
- EV's take more and diverse non-structural materials to develop, making the topic of supply chains very important in the topic of decarbonizaton
- Non-auto oriented travel should be considered when thinking about sustainable transport networks, especially considering the complexities of supply chains surrounding EV

My Reflection

This week we heard a talk by Prof. Elsa Olivetti on the complexity of decarbonization supply chains and the resources and effort it would take to power an EV revolution.

I found the talk very captivating, especially the visualization of distance travelled by minerals before they make it to a vehicle in the US. The presentation made the case for a need to make supply chains for electric batteries more efficient as transport decarbonization takes place and demand for EV's in the US increases. I found her analysis on the difficulties of recycling materials quite interesting, considering that all the minerals discussed were finite in nature and will have an exponential increase in demand.

I was curious, however, about the geopolitical implications of creating transport systems around these finite resources, especially since most of them are imported from the global south to power an EV transition in the global north. From Prof. Olivetti's presentation, it seemed that this movement of minerals is necessary to fight climate change, but externalities of these processes were not discussed. The quest for petrochemicals have caused great geopolitical strife in the world and there seems to be no policy framework to prevent exploitation of nations for these finite minerals. Additionally, decarbonization is a system of tools where technologies developed 100+ years ago (like trains and density) can be very effective in lowering per capita transport emissions while reducing car dependence and its externalities (pedestrian deaths, auto oriented cities etc.). I would have liked to hear more discussion on these topics and whether the complexities of these supply chains are really worth it.