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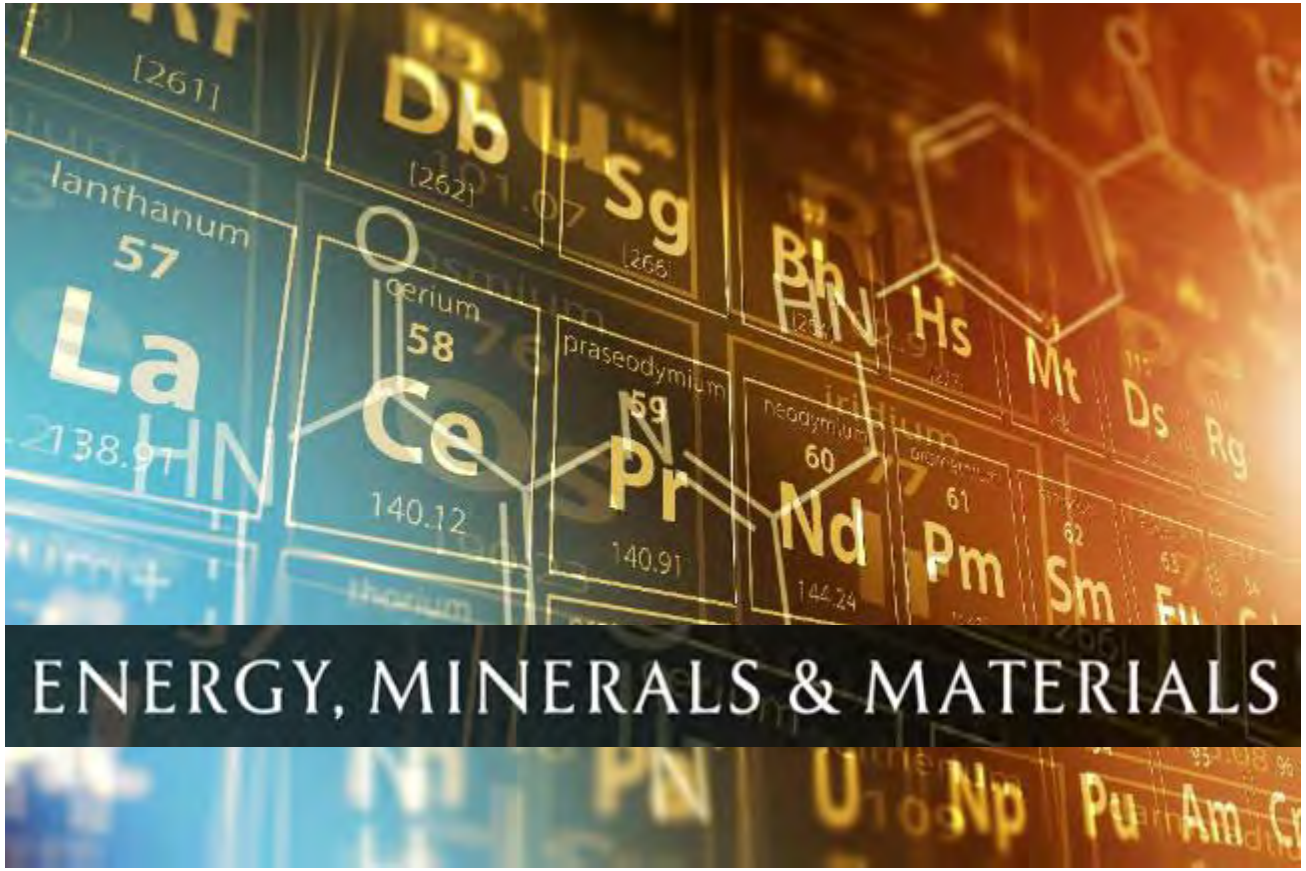
Understanding the Minerals Wild West

Michelle Michot Foss, Ph.D.

IEEJ/APERC, April 25-26 and 27, 2023, Tokyo



https://www.bakerinstitute.org/global-minerals-production-dashboard

https://www.bakerinstitute.org/global-minerals-trade-dashboard

Notes on Compilation

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Several slides represent **Work in Progress** and are marked as such. These are sensitive – we request no outside circulation without permission.

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https://en.wikipedia.org/wiki/It%27s_a_Mad,_Mad,_Mad,_Mad_World

Backdrop

It's a mad, mad, mad, mad world.

Where We Stand, I

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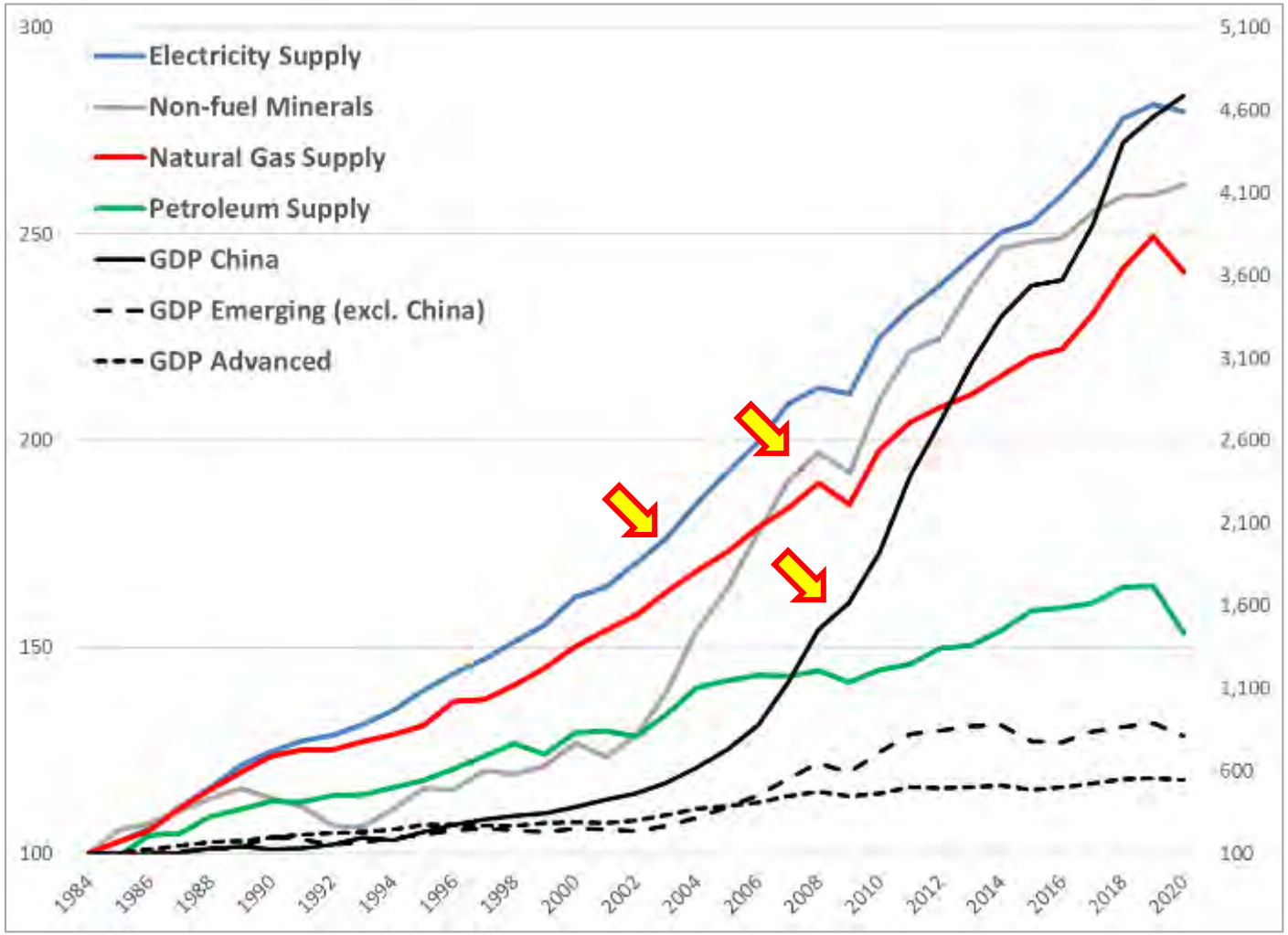

M. Michot Foss using BP, WMC, IMF indexed to 1984. NOTE – GDP on right axis.

Where We Stand, II

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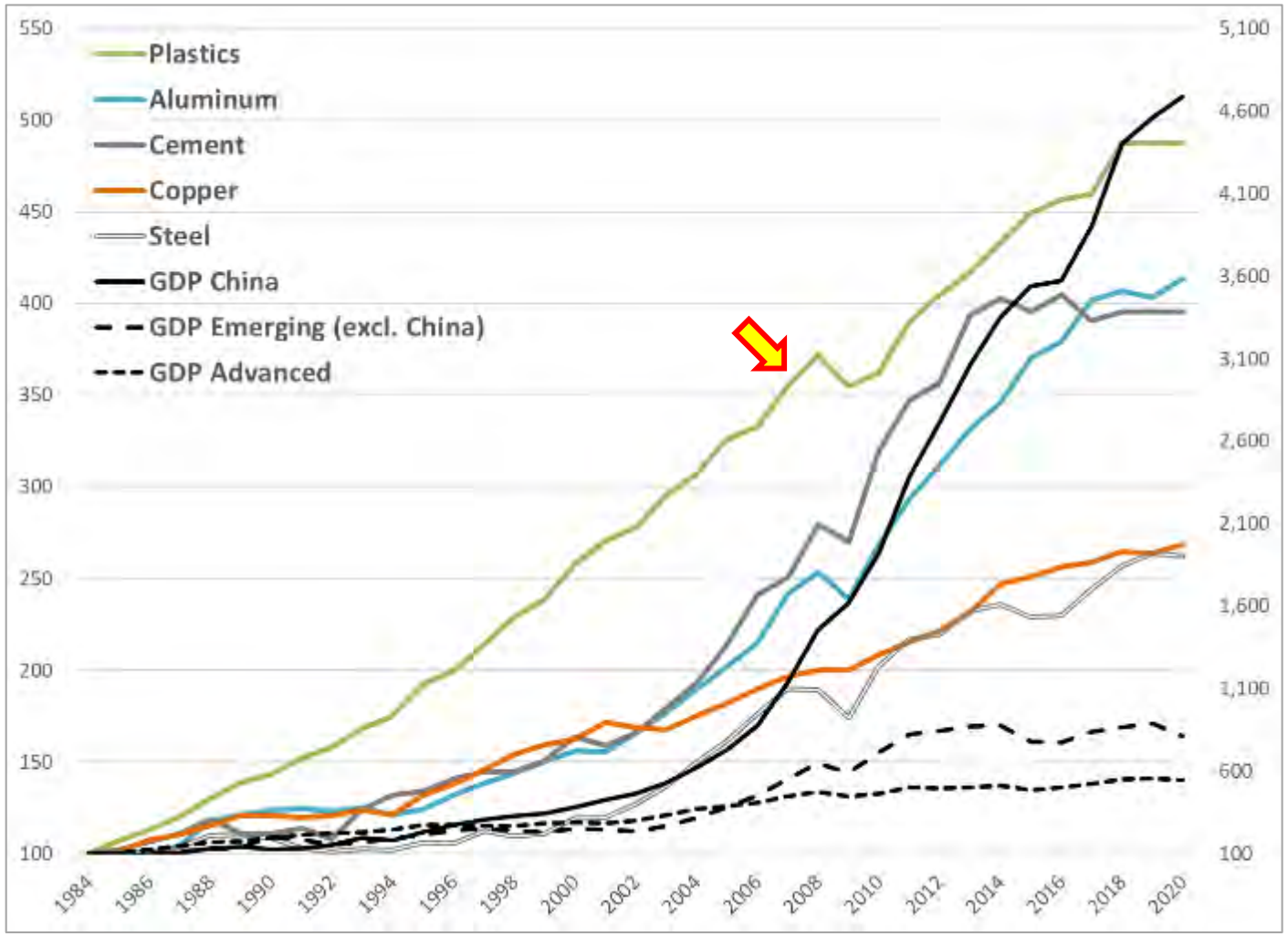

M. Michot Foss using BP, WMC, IMF indexed to 1984. NOTE – GDP on right axis.

The Energy Transition(s) Valley(s) of Death

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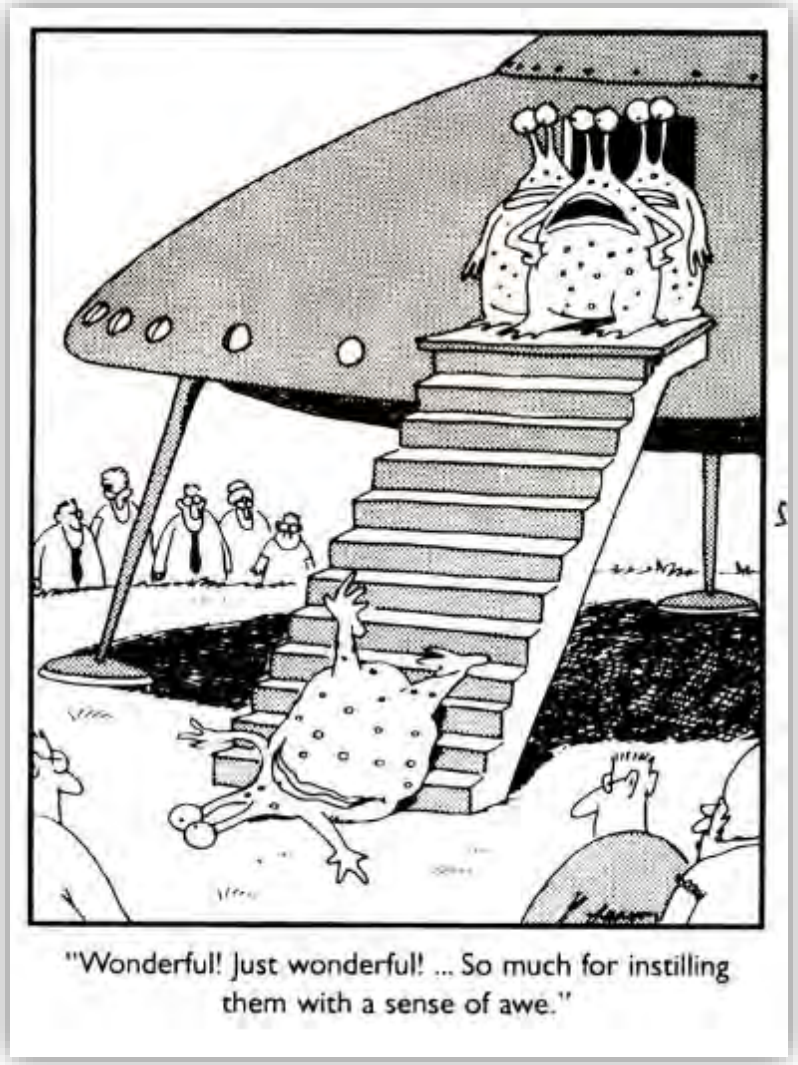

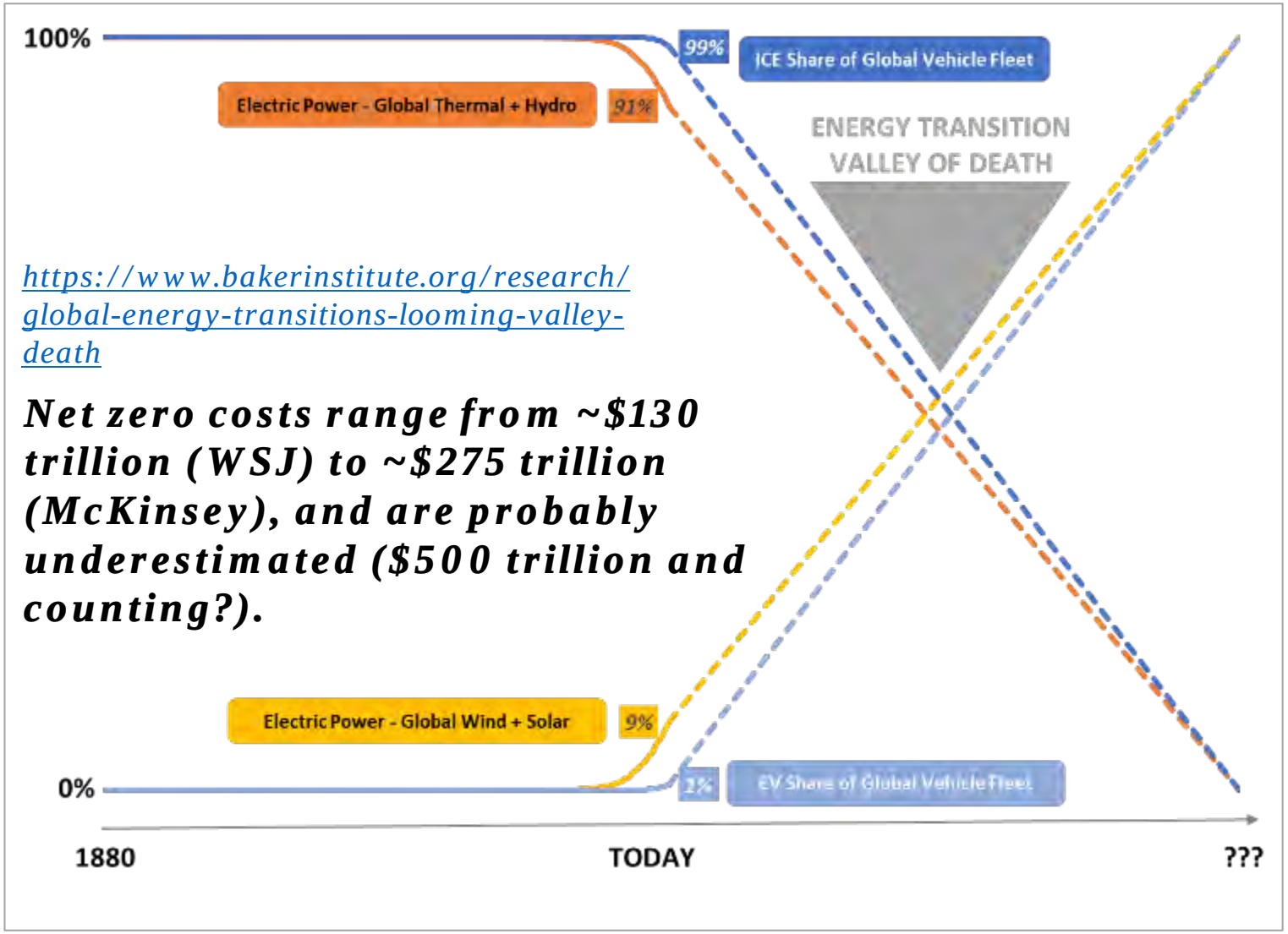

https://www.bakerinstitute.org/research/global-energy-transitions-looming-valley-death

Net zero costs range from ~$130 trillion (WSJ) to ~$275 trillion (McKinsey), and are probably underestimated ($500 trillion and counting?).

The Bet: We can trade off energy density with minerals/materials intensity and come out ahead.

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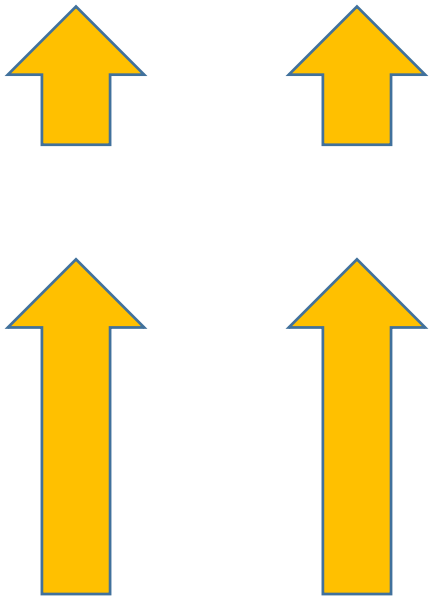
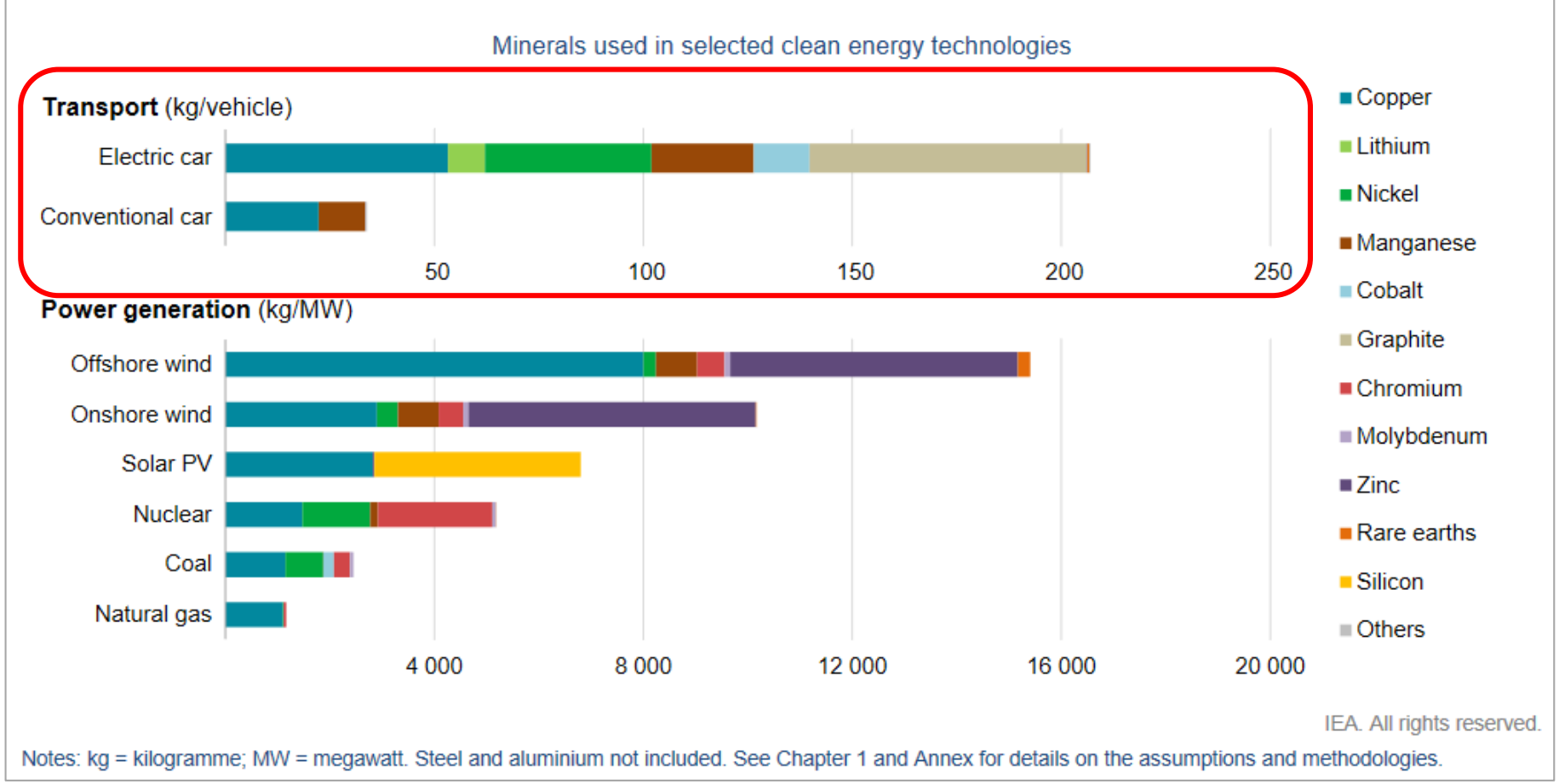
Lower Energy Density ***Higher Materials Intensity***





https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions *Note – author was a peer reviewer.*

Upside Down ~~Renewables~~

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Energy Source	Number of Generators	Number of Generation Locations	Generation per Location ('000 MWh)	Share of U.S. Power Generation	Median Footprint
Natural Gas	6,020 thermal units	1,793	906	40.5%	310
Nuclear	96 reactors	55	14,361	19.7%	5
Coal	668 thermal units	244	3,170	19.3%	1,203
Wind (USGS)	78,008 turbines	1,422	238	8.4%	11,907
Hydro	4,014 dams	153	1,865	7.1%	647
Solar PV (grid)	Unknown	4,599	19	2.1%	1,974
Wood		332	109	0.9%	47,048
Geothermal		170	93	0.4%	46
Solar CSP		18	174	0.1%	1,319

://docs.wind-watch.org/US-footprints-Strata-2017.pdf
://journals.plos.org/plosone/article?id=10.1371/journal.pone.0270155#sec009%20

Commercial Battery Chemistries

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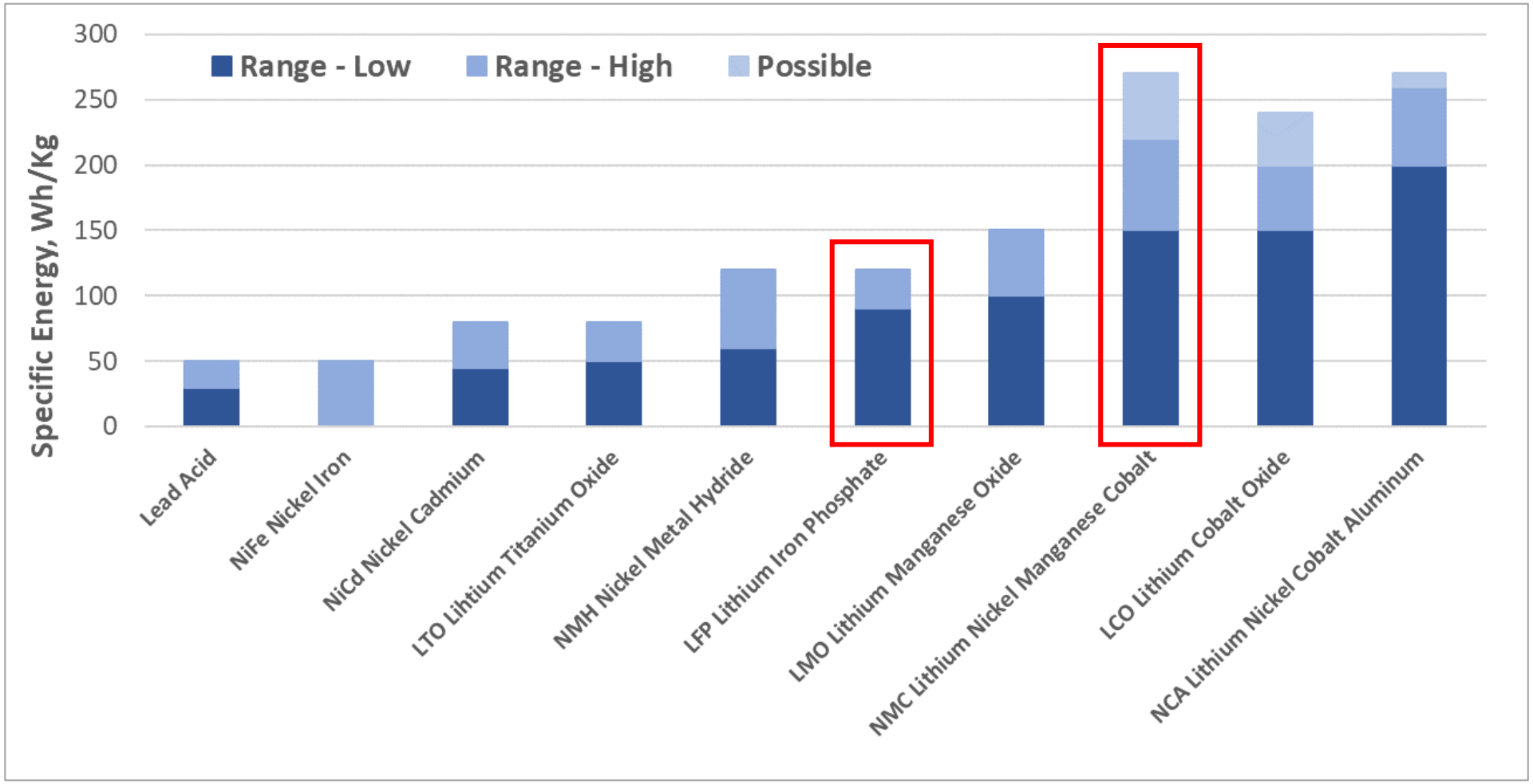
Gasoline = ~12,500 Wh/Kg



Work in Progress

Fuel and Non-fuel Minerals Output

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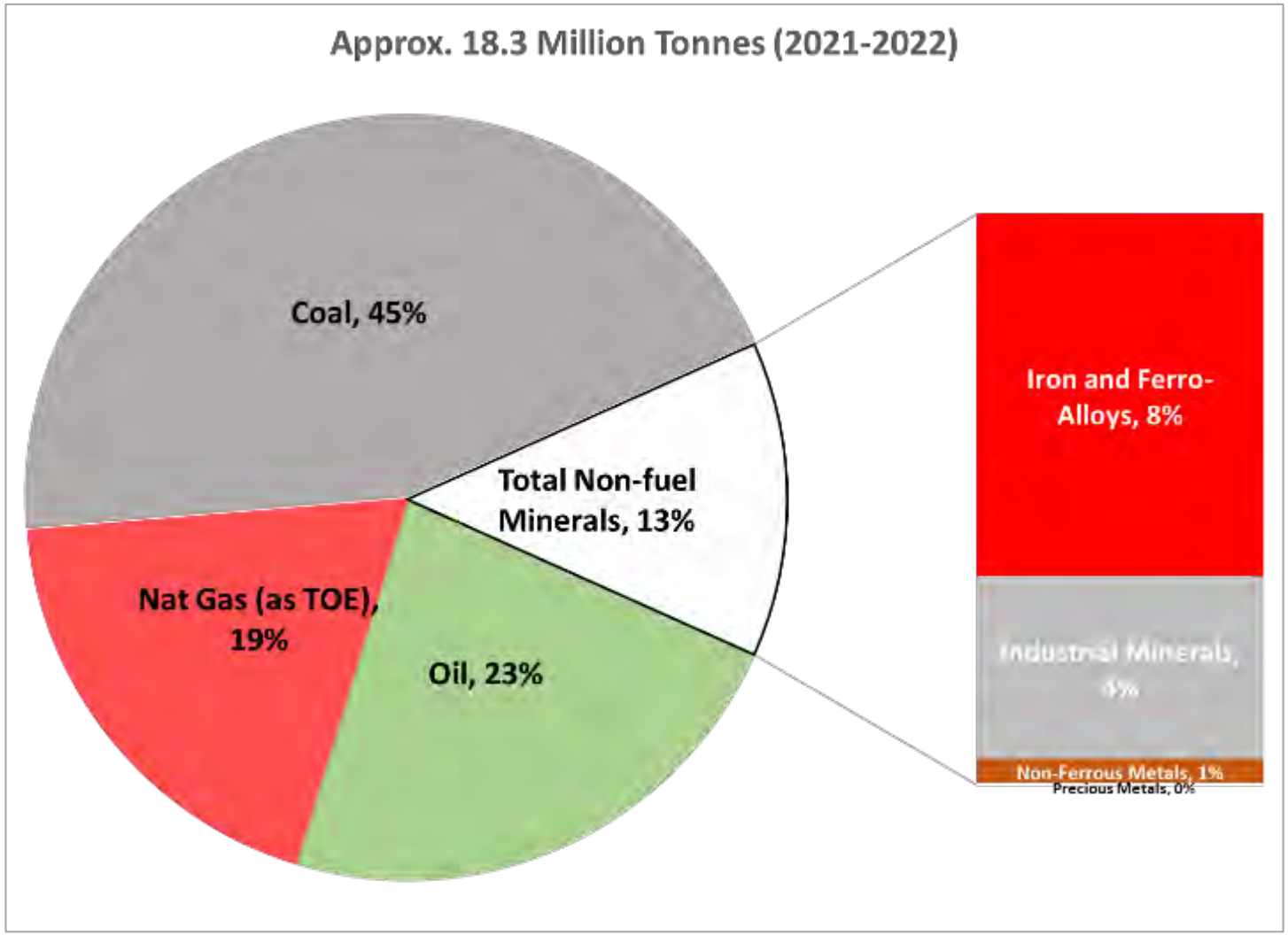
- In “net zero” scenarios both the energy equivalent **AND** intrinsic energy storage attributes of fossil fuels must replaced.
- Battery metals and materials **ONLY** provide energy storage.
- Energy must be provided from other sources in the equivalent of fossil fuels commitments **IF** fossil fuels are to be displaced.
- **ALL** non-fuel minerals will be needed, not just battery metals and materials.
- See WMD for nf minerals classifications.



Work in Progress

Fuel and Non-fuel Minerals Market Values

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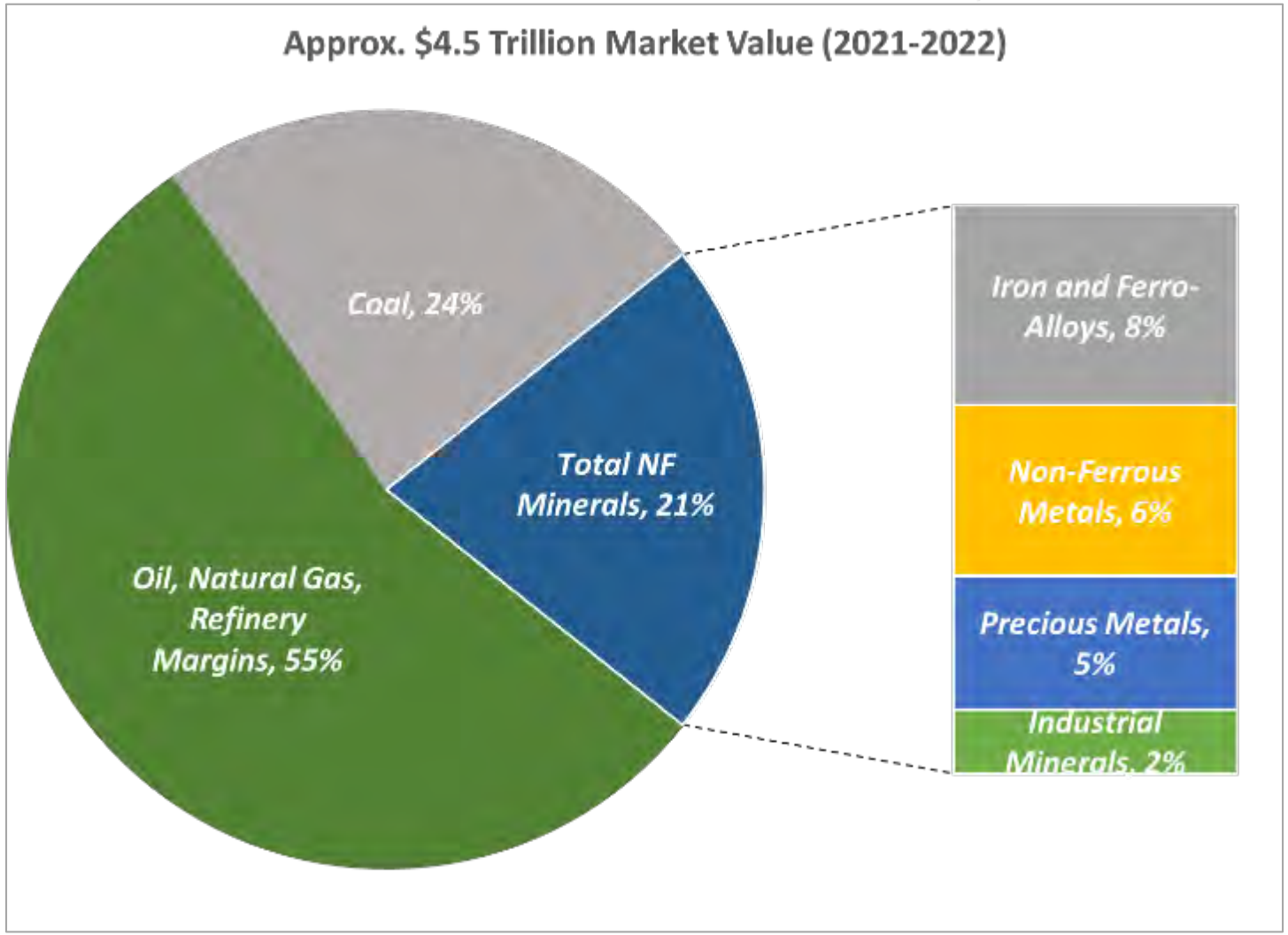

MM Foss using BP, WMD, EIA and other. Work in progress. Note that market values are for crude oil, natural gas and average refining margins. Excludes bauxite.

Work in Progress

All of the growth fit to print…

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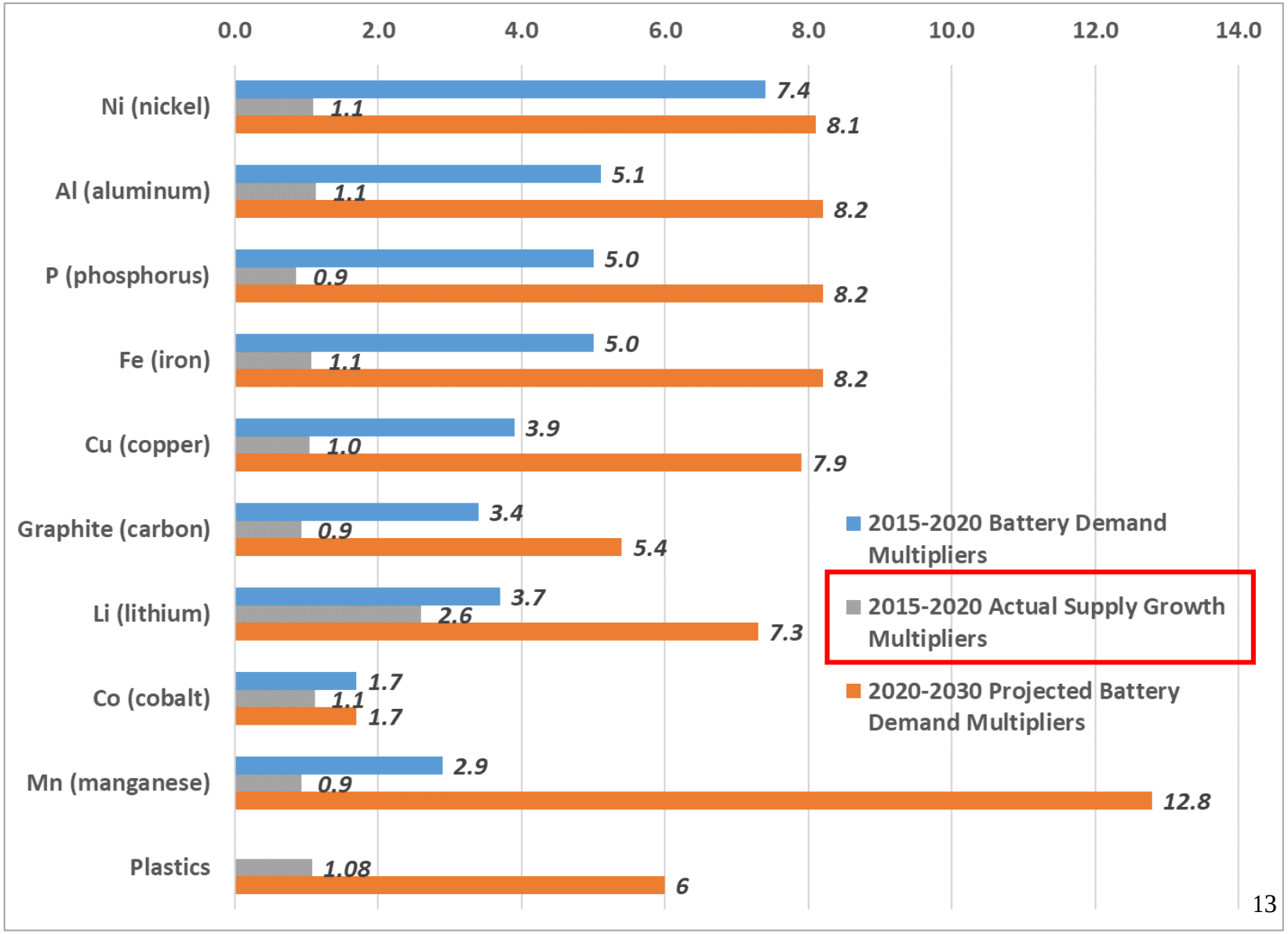
- Demand multipliers reflect growth **ONLY** from EV production.
- BNEF expects **passenger EVs to grow from 53% to 67% of battery market in 2030**, with other EVs at 24% and non-transport use (incl. stationary storage) 9%.
- Metals for batteries could "crowd out" metals for other uses.



2015-2020 actuals (total minerals supply) based on CES baseline. Demand multipliers from BNEF. Plastics estimated by author.

Minerals Investment Context

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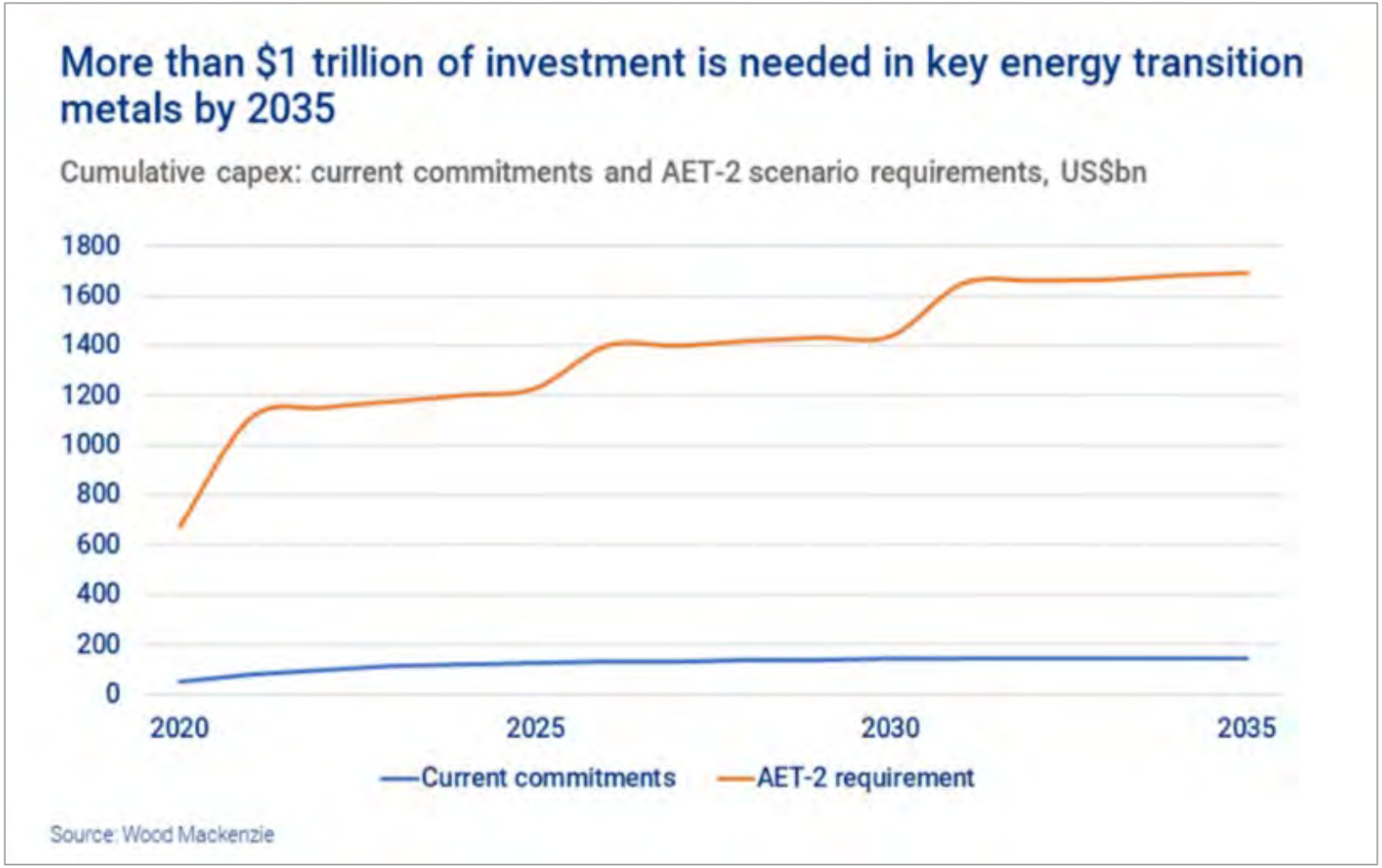

https://www.woodmac.com/news/opinion/faster-decarbonisation-and-mining-a-crisis-of-confidence-or-capital/

Follow the Money: Nickel Example

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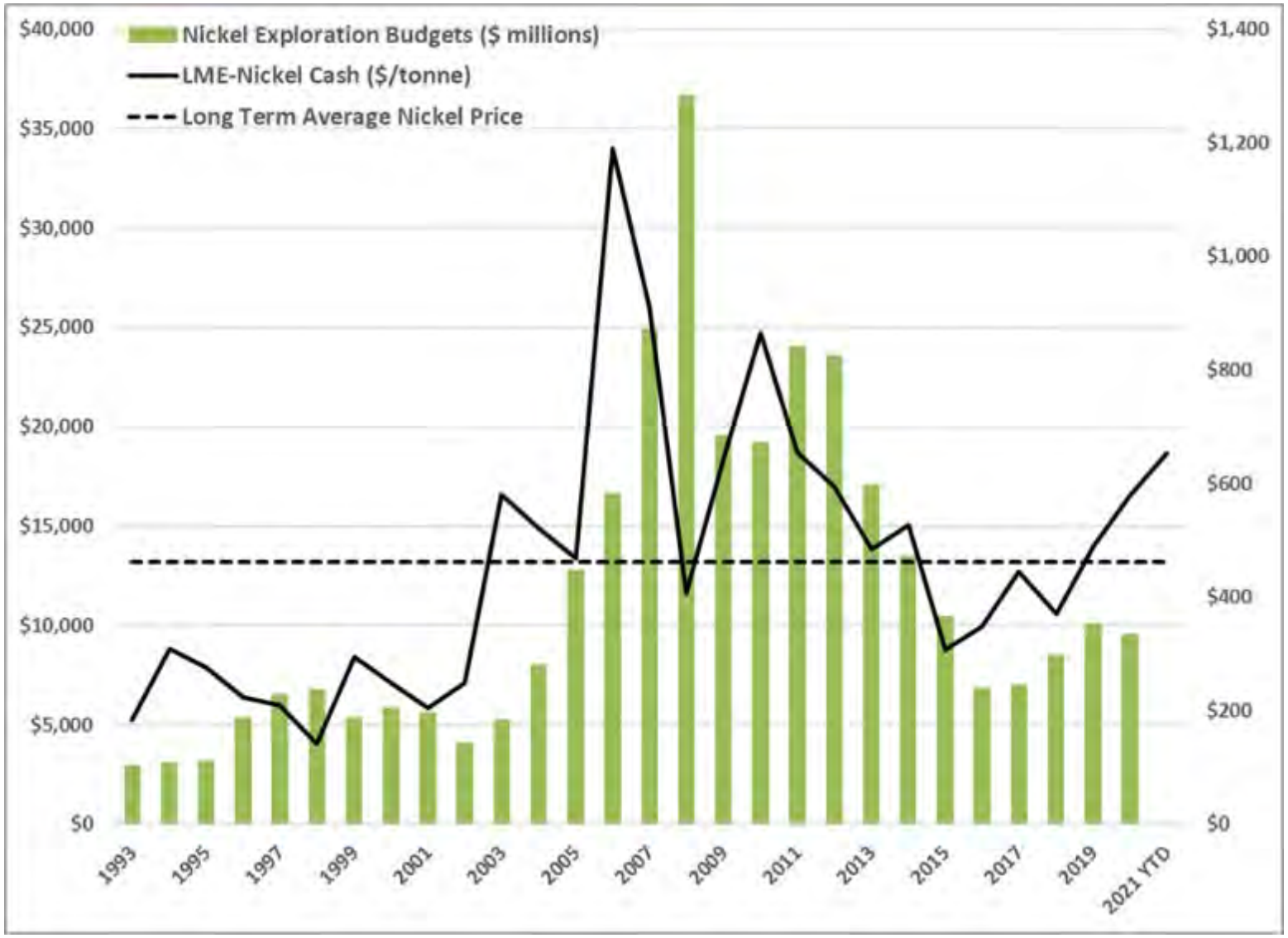
Exploration budgets are contingent on risk-weighted expected returns, sensitive to price.



Author analysis based on SPG, accessed via license.

An undercapitalized industry struggles to spend…

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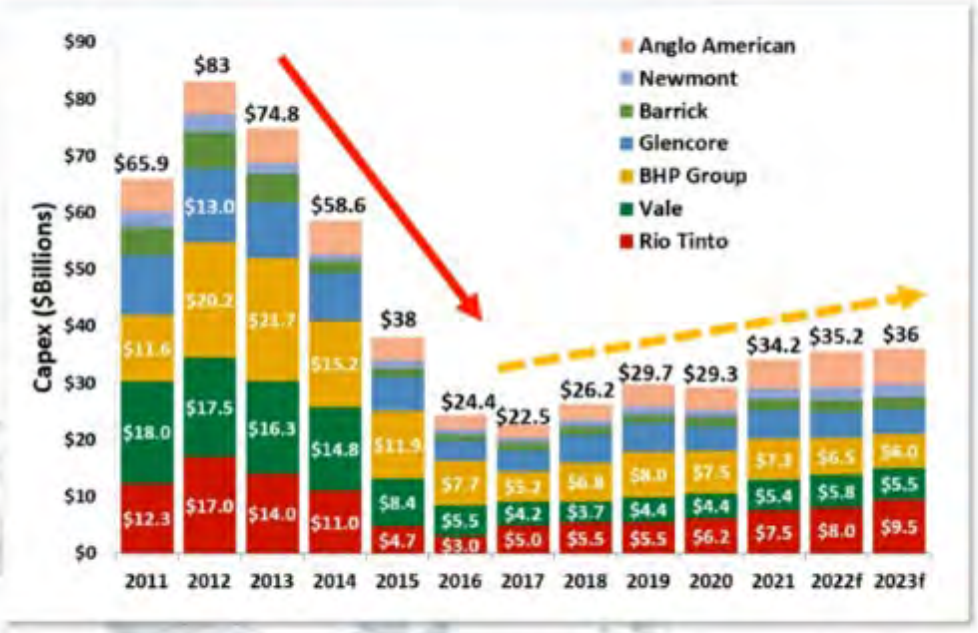
Major Mining Company Capital Expenditures

Capex Spending by Year 2011 – 2023

Sponsored By:



- Capex up 3% in 2022 and 2% in 2023
- 52% increase in spending 2017-2021
- These 7 companies account for about 10% of the active projects

- Strategic production capex / increase in underground investment.
- Mine expansions over grassroot.
- Expect scaled investments into energy transition metals & minerals.
- With focus on cost management/margin improvement investments.

Industrial Info Resources

...while investors struggle to stick with the (net zero, ESG) program.

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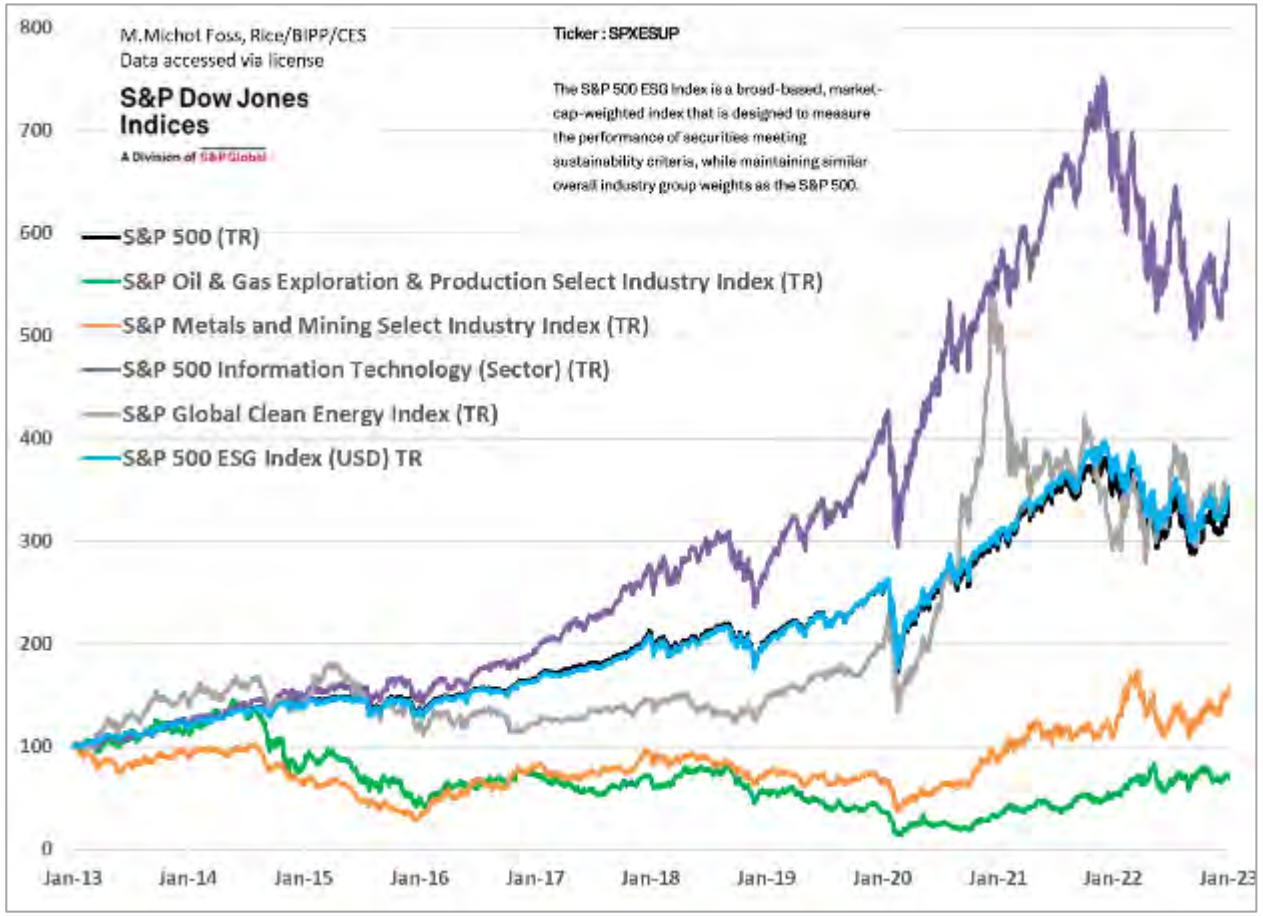
*The Revenge of the Old Economy

1-Year Total Return



*Jeff Currie, for FT, Oct 21, 2021 https://www.ft.com/content/c7732d53-2e34-4fde-b5fb-6f45f114111f

What's in a name?

Critical Minerals/Mining Industry Challenges

Work in Progress

Who's on first?

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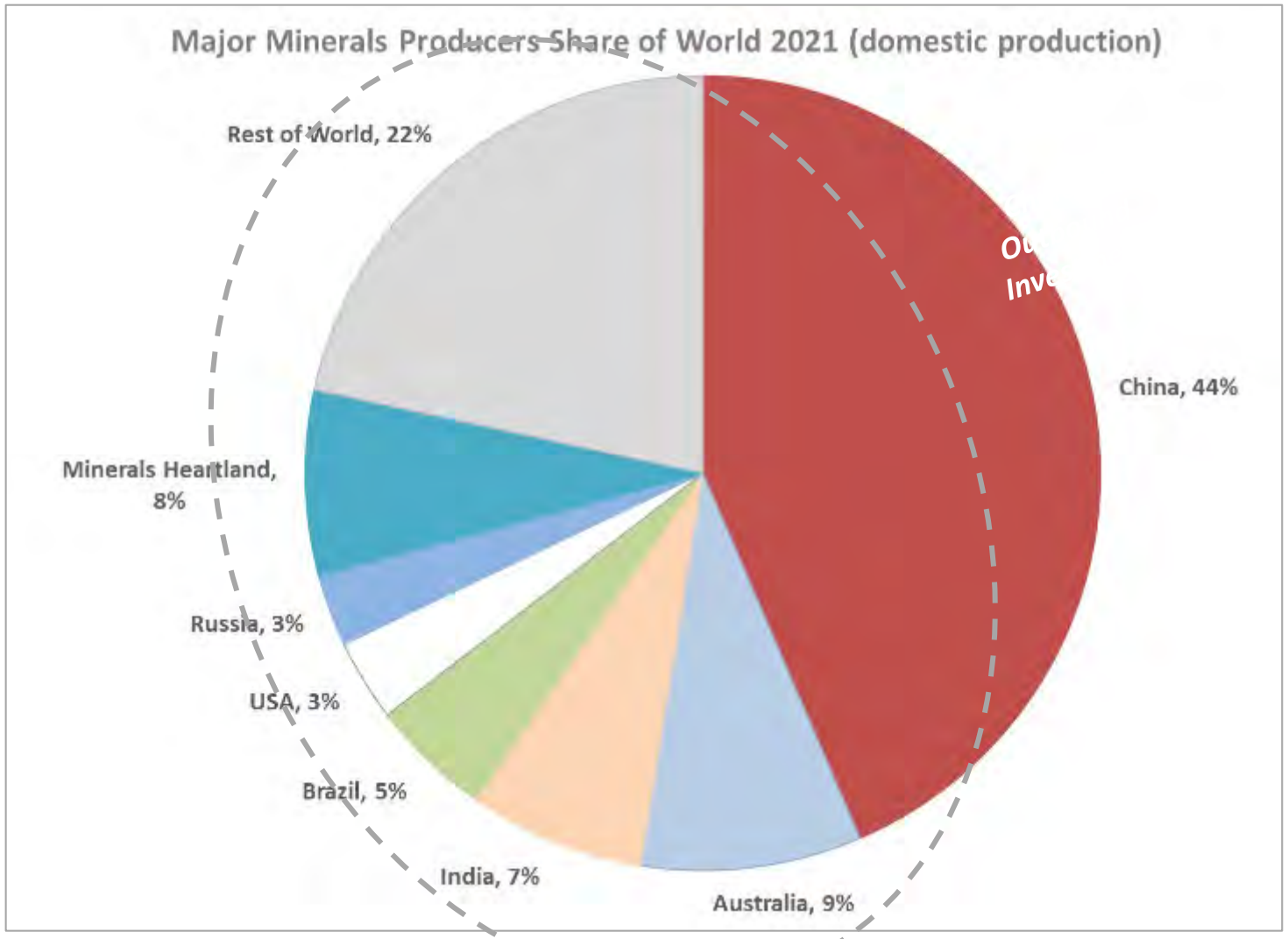

China controls:

- More than 90% each of gallium and germanium;
- **80% of rare earth materials with new SOE**;
- 70% of graphite/graphene;
- 60% of lithium;
- Nearly 60% of vanadium;
- 41% of indium;
- 36% of cobalt;
- 50% or more of copper refining with comparable shares for other metals;
- International trade (copper, lithium, nickel and other);
- ~60% of wind turbines manufacturing;
- ~70% of solar PV output;
- **~70-80% or more (90+% of announced) of large format battery manufacturing capacity (NMC, LFP).**

Chart based on USGS as compiled by CES, Minerals Heartland is Africa, Middle East, Central Asia; China shares based on FP Analytics and other sources as compiled by CES

Work in Progress

How Battery Mfg Capacity Stacks Up

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	World	China	China Share of World
NMC Chemistry (where known)			
Fully Commissioned	368	257	70%
Under Construction	299	252	84%
Announced	502	502	100%
% NMC of World, China Total Battery Chemistries (based on Table 2)			
Fully Commissioned	55%	50%	
Under Construction	31%	30%	
Announced	27%	63%	
LFP Chemistry (where known)			
Fully Commissioned	89	85	96%
Under Construction	164	164	100%
Announced	77	74	97%
% LFP of World, China Total Battery Chemistries (based on Table 2)			
Fully Commissioned	13%	16%	
Under Construction	17%	20%	
Announced	4%	9%	

Source: Compiled by authors using BNEF inventory, accessed via license.
www.bakerinstitute.org/sites/default/files/2022-04/import/research-paper-nickel-041122.pdf

Closer Look: REE

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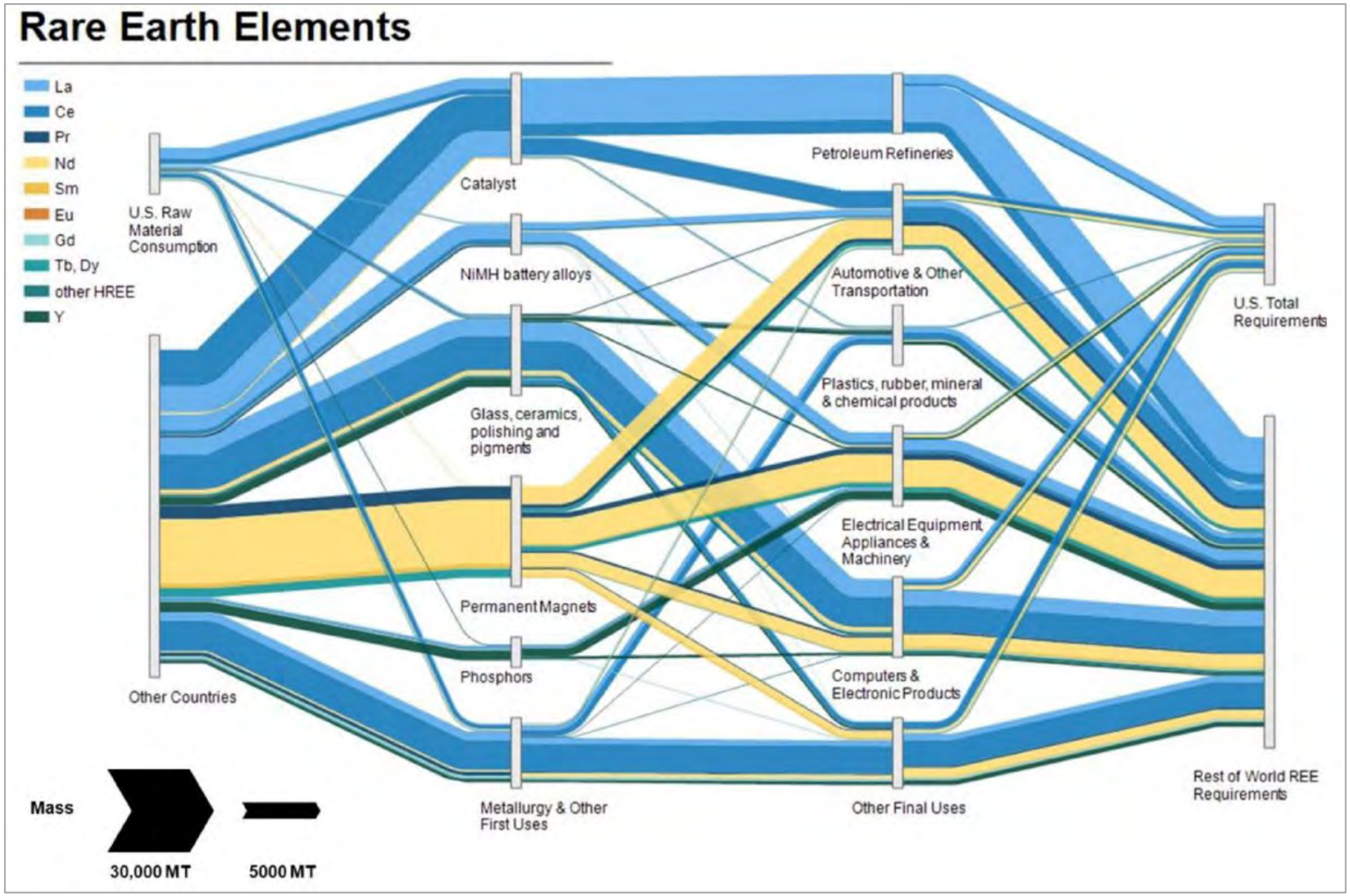

https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.13354

China REE: The Power of Quotas

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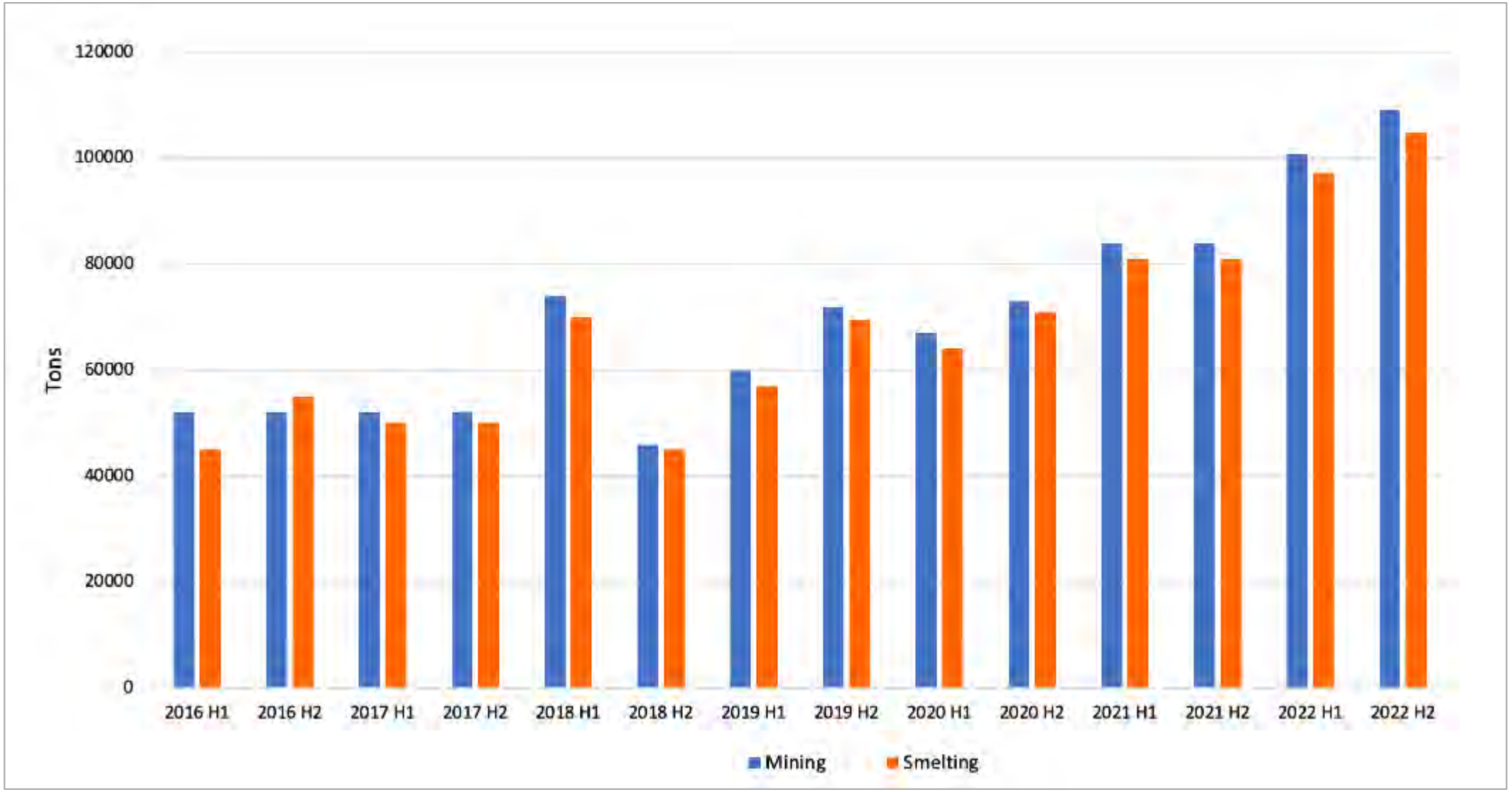

www.bakerinstitute.org/research/chinese-behemoths-what-chinas-rare-earths-dominance-means-us

China REE: Monoliths

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Entity	Subscribed Capital	Shares Ratio
SASAC (State-owned Assets Supervision and Administration Commission of the State Council)	RMB 31.21 million	31.21%
CHINALCO	RMB 20.33 million	20.33%
China Minmetals Co.	RMB 20.33 million	20.33%
China Southern Rare Earth Group	RMB 20.33 million	20.33%
China Iron & Steel Research Institute Group	RMB 3.9 million	3.9%
Grinm Group Co.	RMB 3.9 million	3.9%

Policy	Global Supply	International Price	Chinese Price	Resilience
Illegal mining and export	Increase	Decrease (Negative effect)	Decrease (Negative effect)	Improve/strengthen
Chinese environmental regulations	Weaken	Increase (Positive effect)	Increase (Positive effect)	Demote/weaken
Consolidation of rare earth enterprises	Weaken	Increase (Positive effect)	Increase (Positive effect)	Demote/weaken
State-sponsored stockpiling	Weaken	Increase (Positive effect)	Increase (Positive effect)	Demote/weaken

www.bakerinstitute.org/research/chinese-behemoths-what-chinas-rare-earths-dominance-means-us

New Turf

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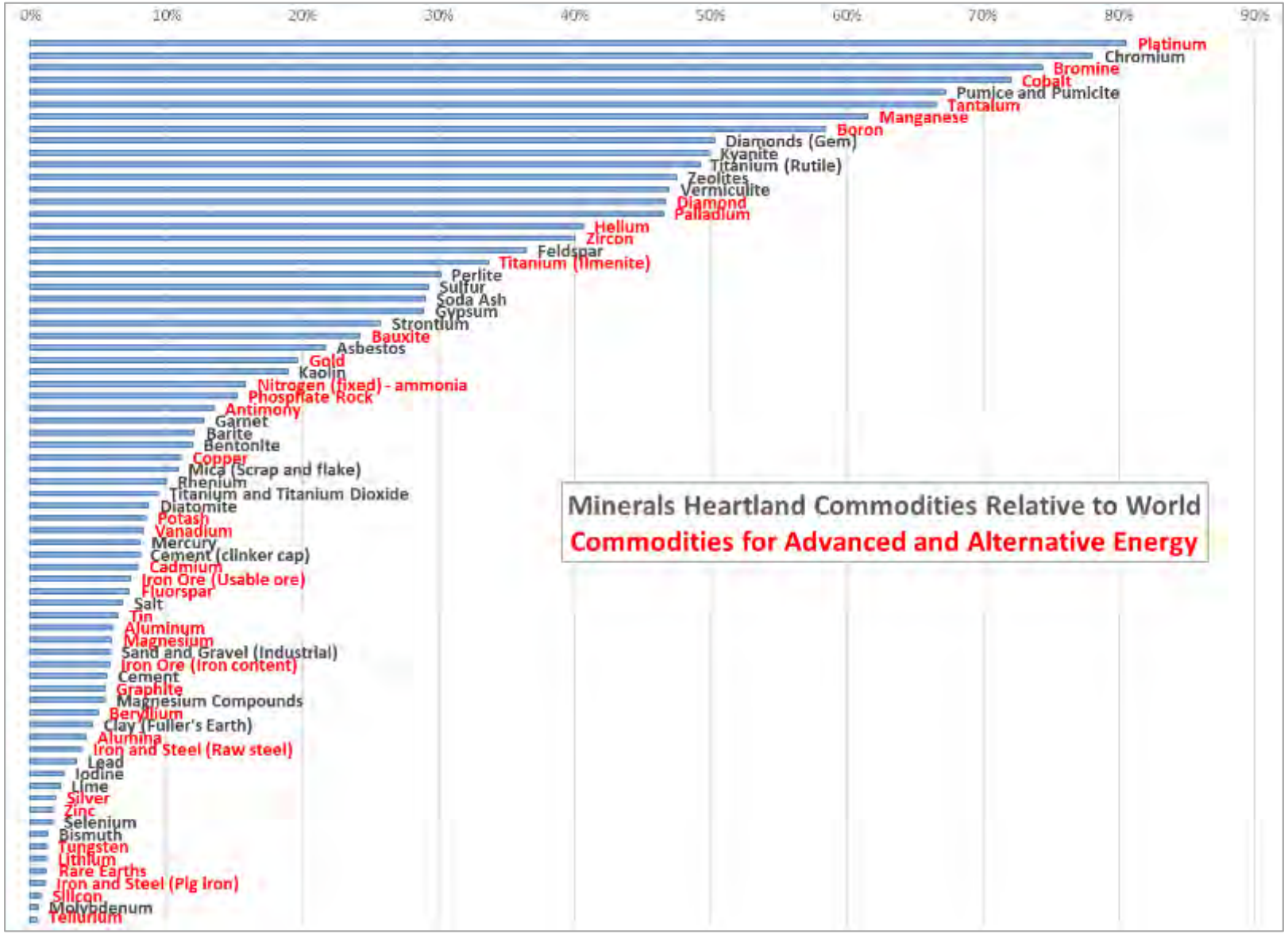
https://www.bakerinstitute.org/research/defining-minerals-heartland-future-africa-central-asia

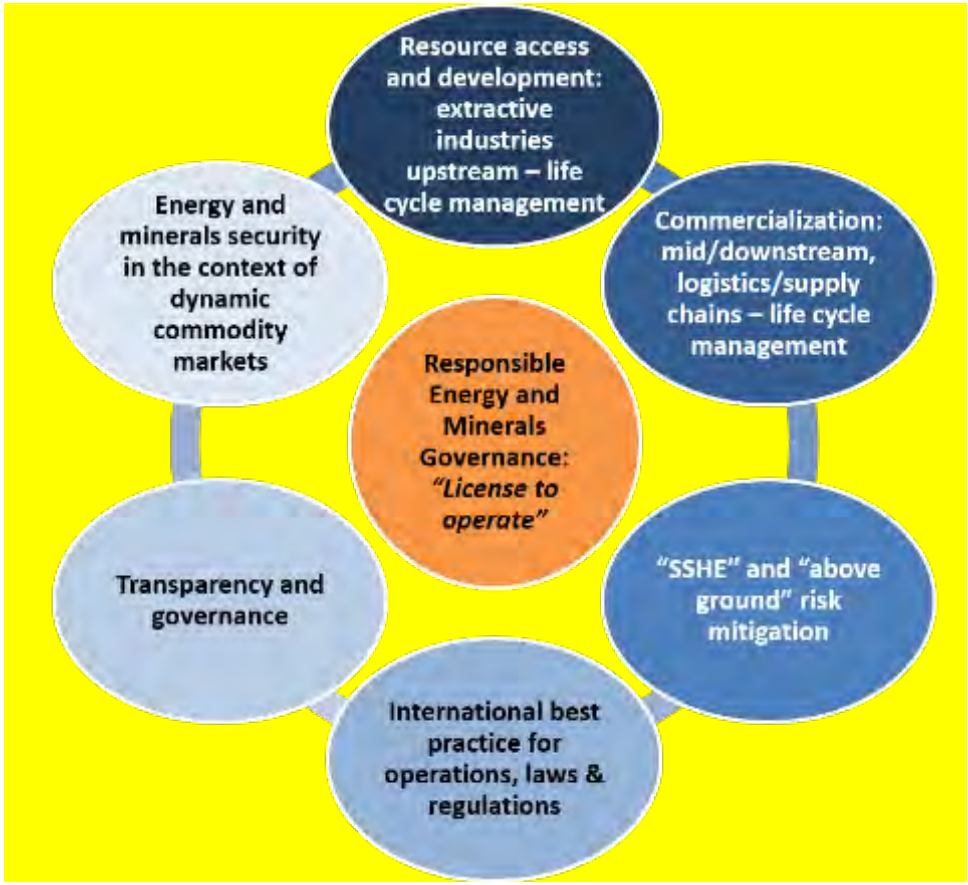


Build cognizance of supply chain and life cycle risks and uncertainties

- From raw materials ***sourcing*** to ultimate ***end of life*** management
- Attend to ***economic, environmental, geopolitical security risks and uncertainties***
- Technology and policy approaches for ***responsible development and use***
- ***Can it be done profitably???***

Bingham Canyon Copper Mine, Utah

"All value chains begin upstream"



M. Michot Foss

Commercial Frameworks

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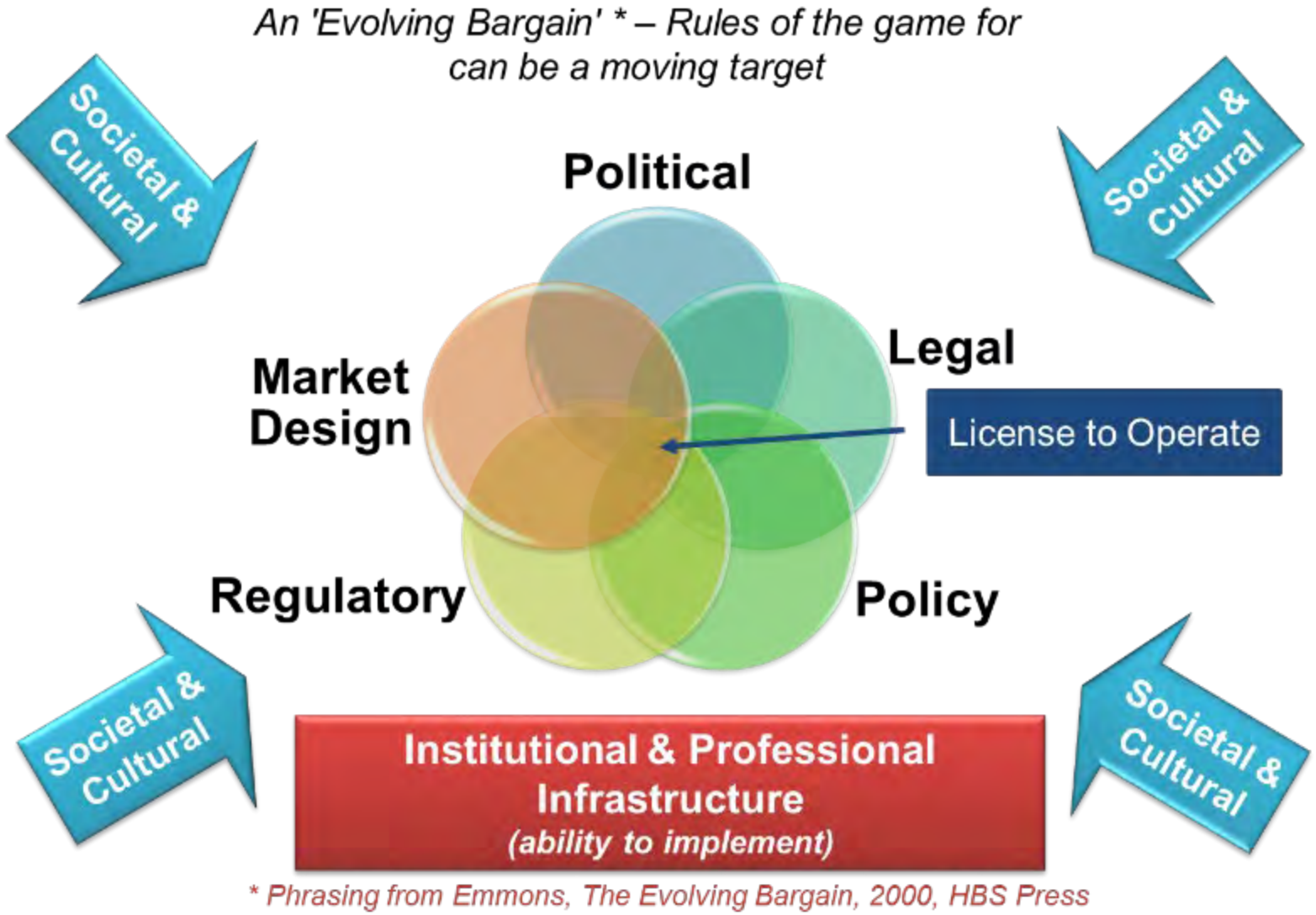
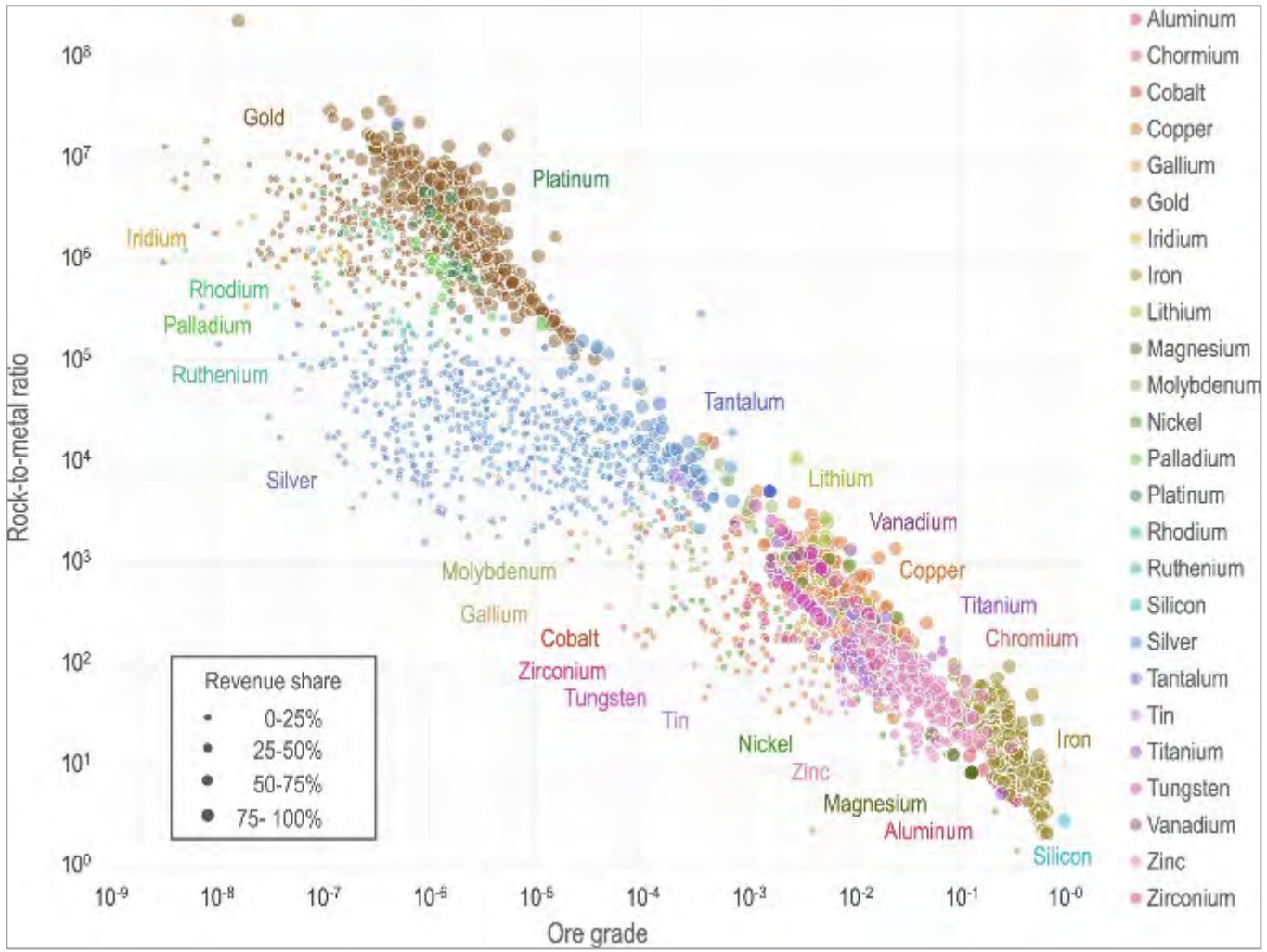
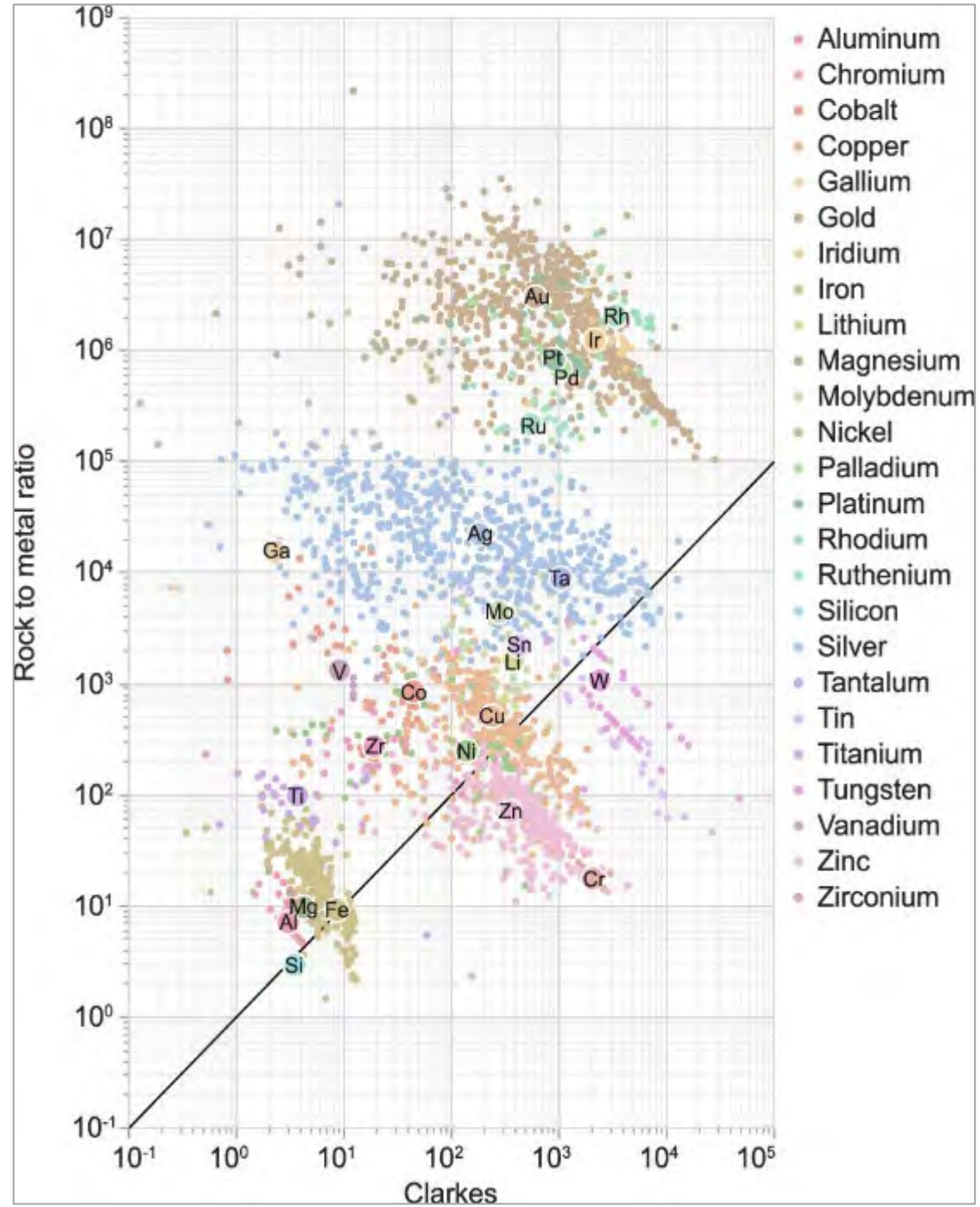


Challenge of Minerals Occurrence





Work in Progress

Challenge of Commercialization

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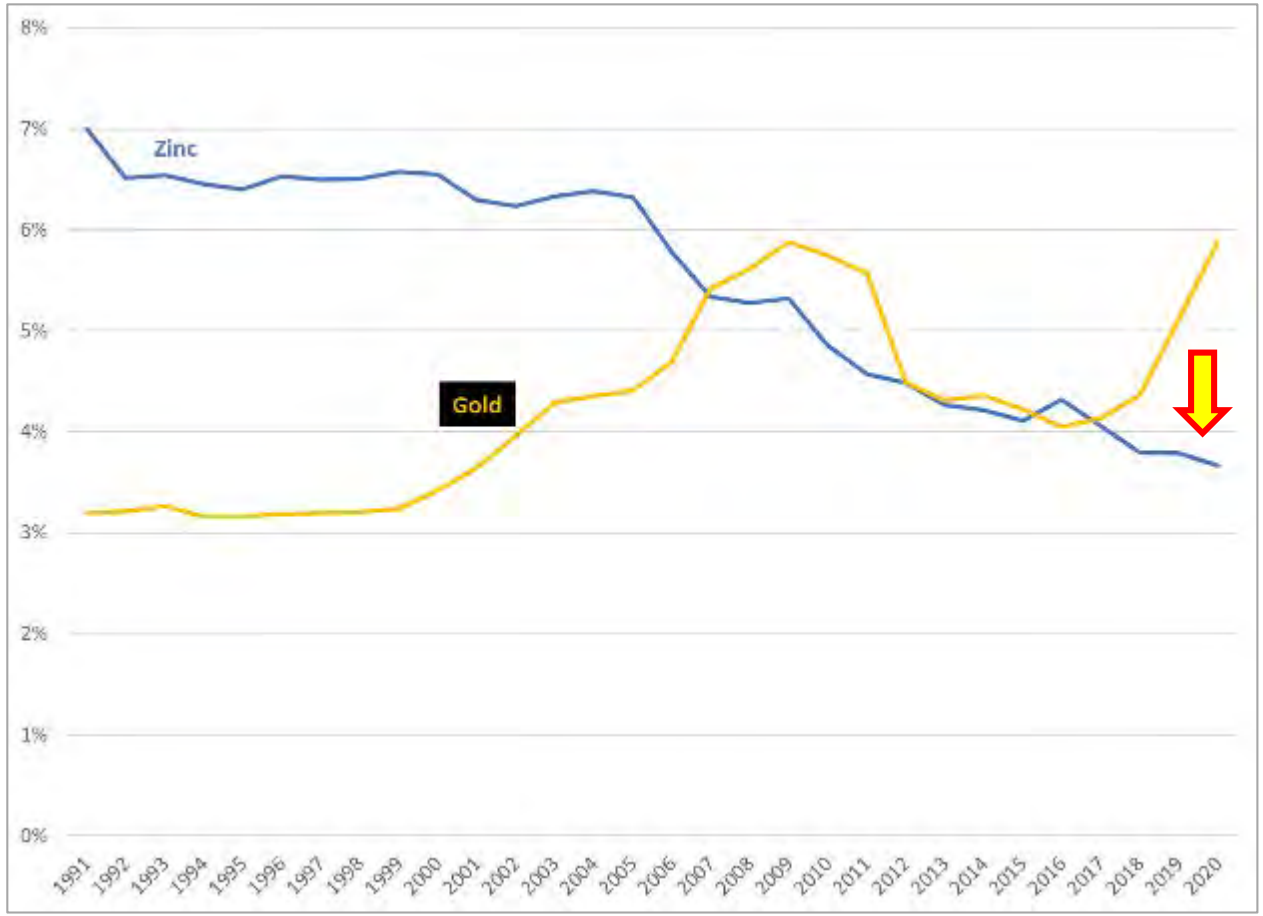
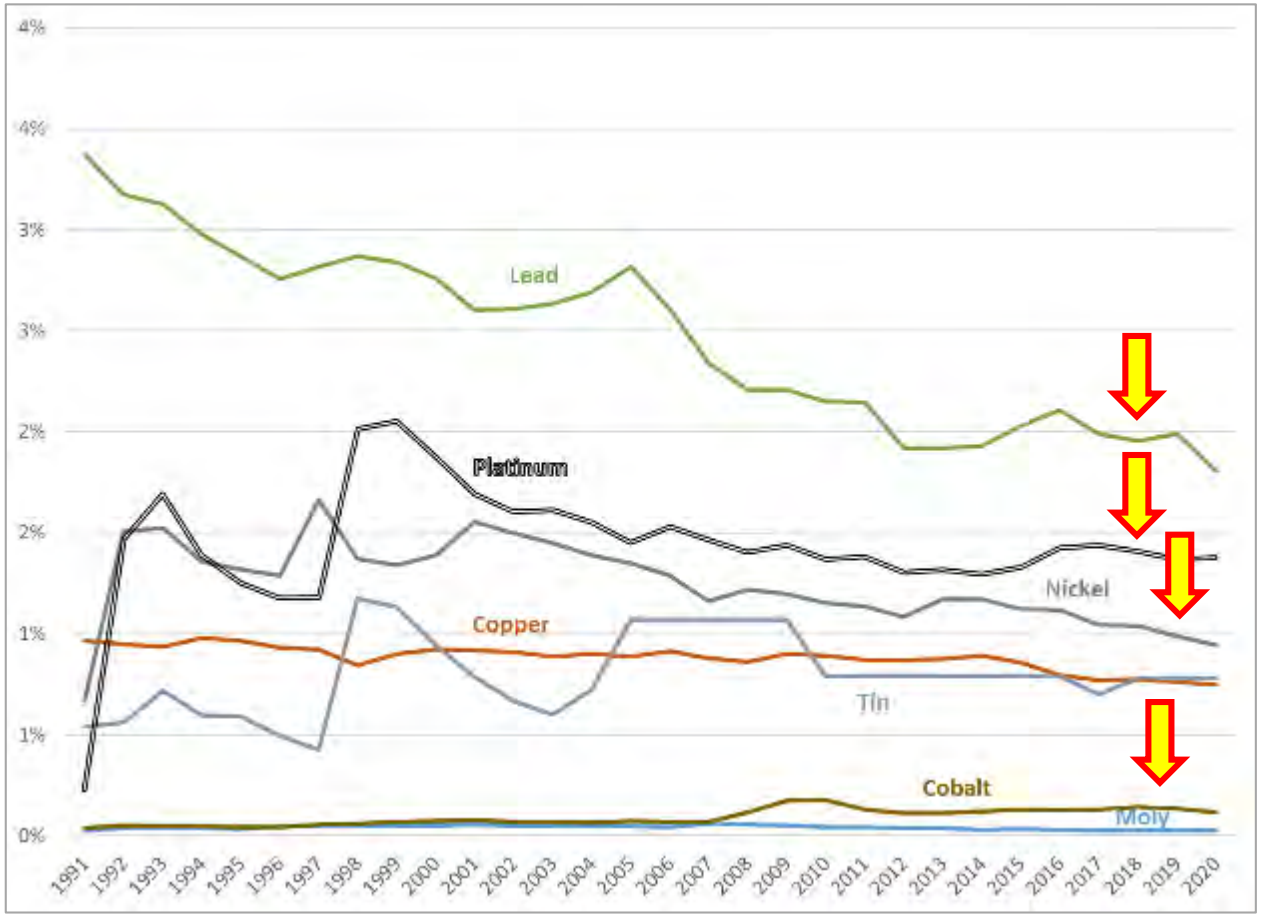
Historical head grades from operational data.





Michot Foss based on SPG MI (SNL), accessed via license.

Challenge of Waste

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See nickel case study in Lagniappe

"The world is full of red muds." Yet-Min Chiang, MIT @ DOE ARPA-E summit, May 2022, Denver.

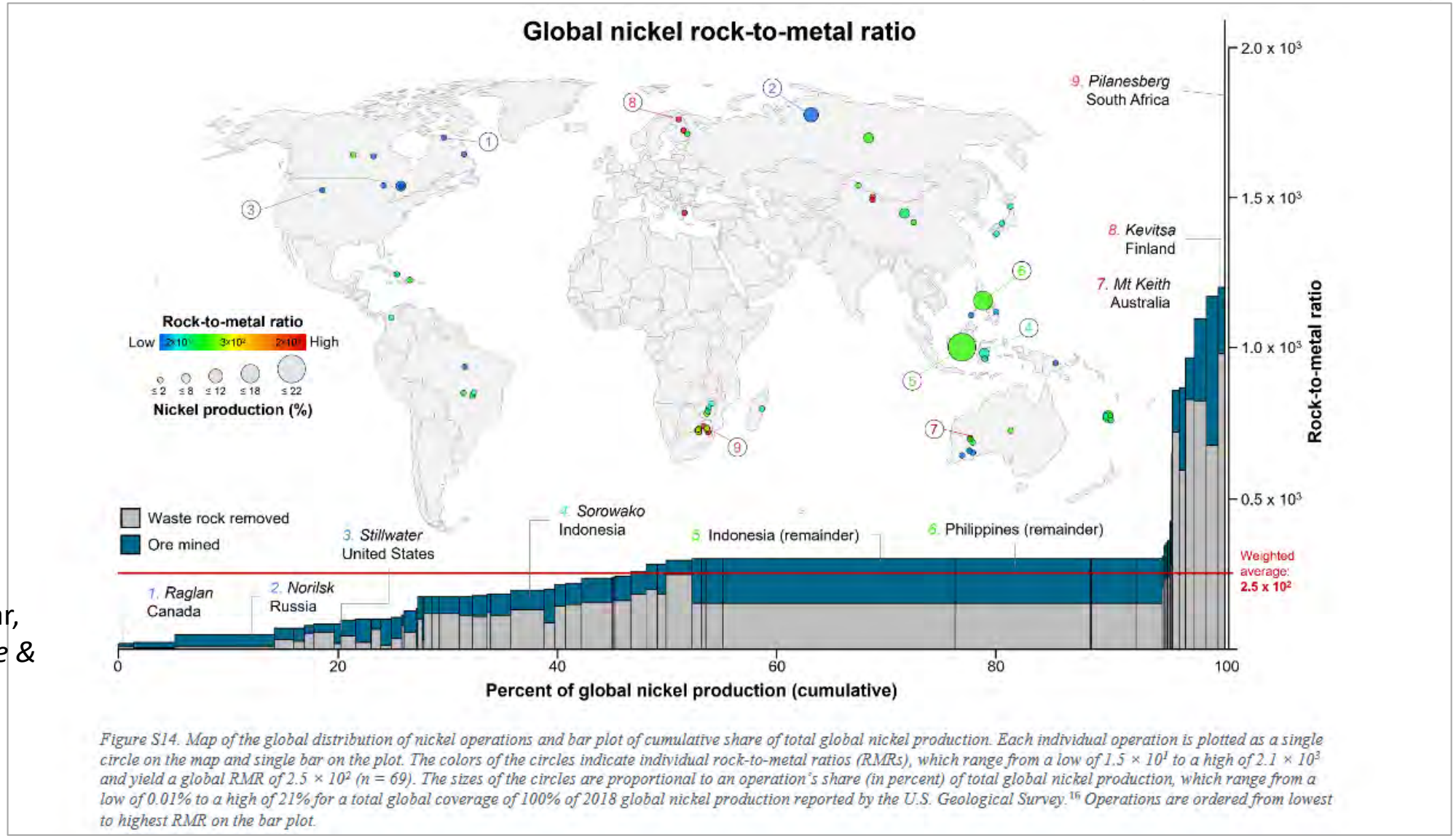

Figure S14. Map of the global distribution of nickel operations and bar plot of cumulative share of total global nickel production. Each individual operation is plotted as a single circle on the map and single bar on the plot. The colors of the circles indicate individual rock-to-metal ratios (RMRs), which range from a low of 1.5 × 10¹ to a high of 2.1 × 10³ and yield a global RMR of 2.5 × 10² (n = 69). The sizes of the circles are proportional to an operation's share (in percent) of total global nickel production, which range from a low of 0.01% to a high of 21% for a total global coverage of 100% of 2018 global nickel production reported by the U.S. Geological Survey.[16] Operations are ordered from lowest to highest RMR on the bar plot.

Rock-to-Metal Ratio, Nassar, et al, *Environmental Science & Technology* **2022** *56* (10), 6710-6721, DOI: 10.1021/acs.est.1c07875

Challenge of Sustaining Supply: Copper

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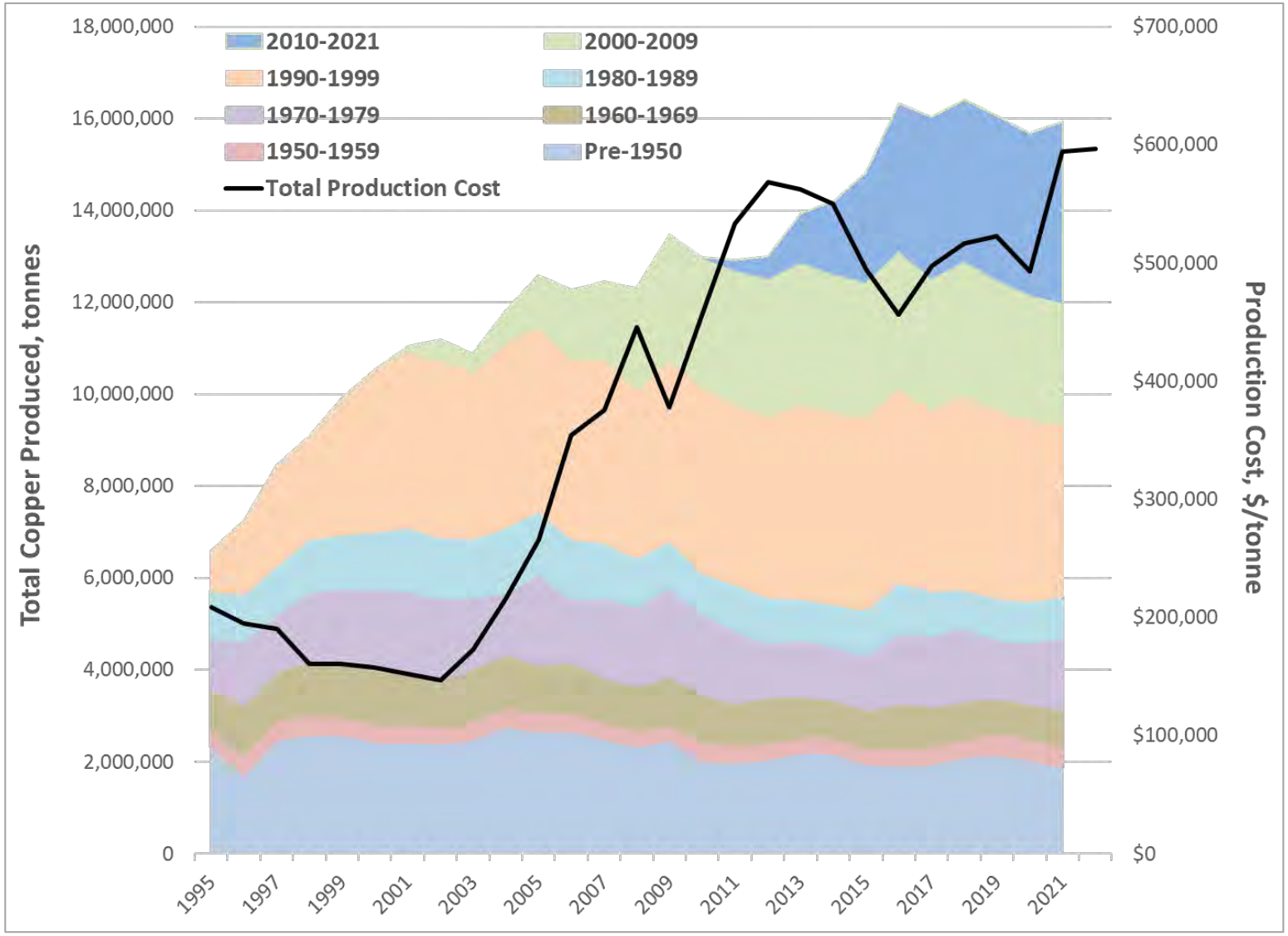
- Vintaged copper supply stack captures ~80% global production.
- **Nearly 40% of current output is from assets older than 1990.**
- Many of these are not "ESG compliant".
- Many of the largest, older assets remain in operation because decommissioning not practical.
- As assets age, ore grades decline, paid metal to waste, rock to metal ratios deteriorate.



MM Foss using SPG, accessed via license. Work in progress.

NIMTO = "not in my term of office"

Challenge of Project Cycle Times

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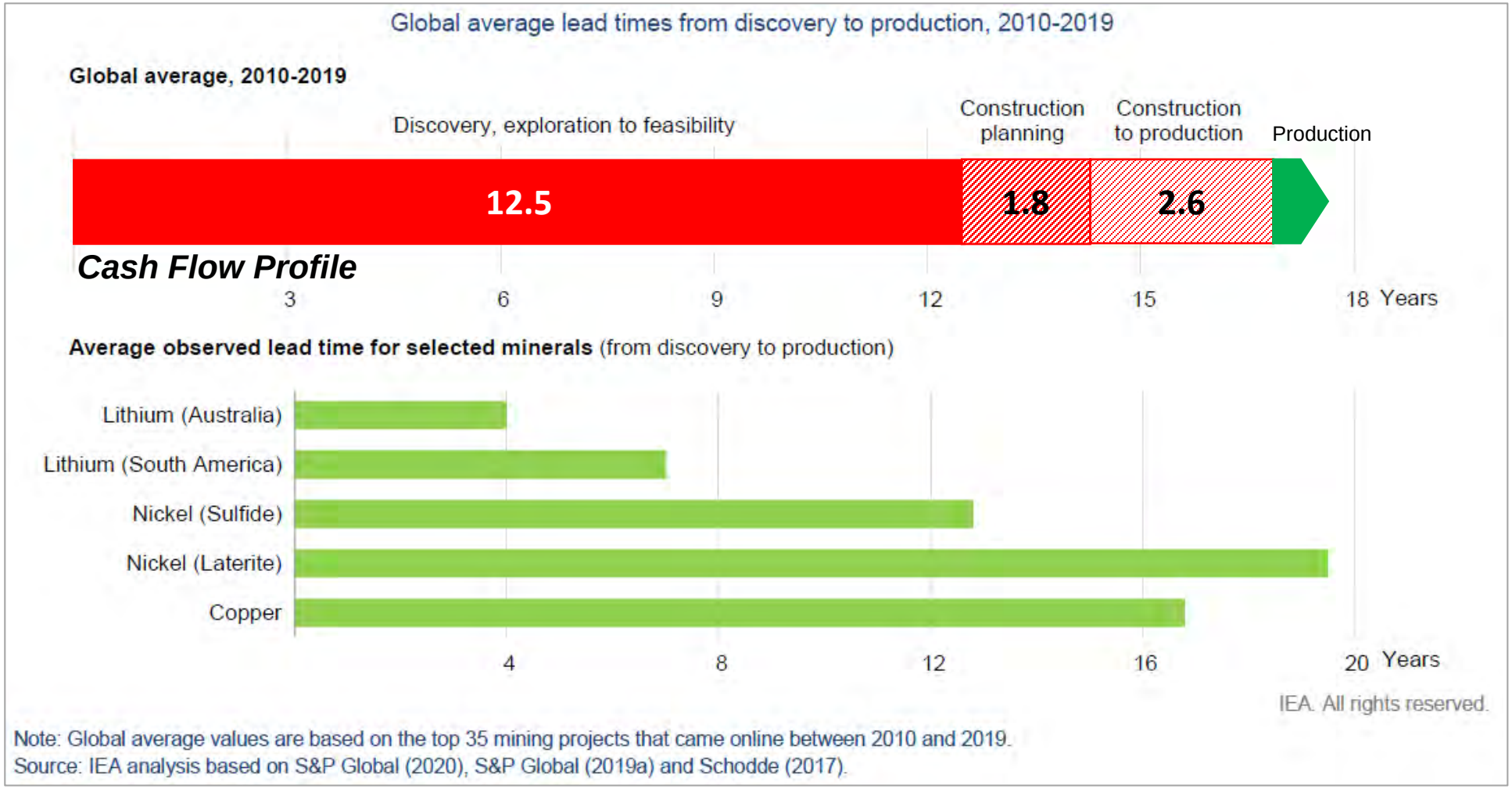
"U.S. Mining: Heightened Risks Of Regulatory Changes As Resource Nationalism Intensifies Globally"

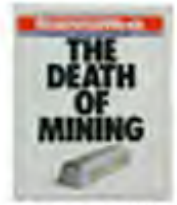
Fitch Solutions / Mining / United States / Tue 12 Oct, 2021
https://www.fitchsolutions.com/mining/us-mining-heightened-risks-regulatory-changes-resource-nationalism-intensifies-globally-12-10-2021



https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

Why have U.S. smelters shutdown?

- Many smelters were built close to ore bodies. When ore was exhausted, smelter was not located near low-cost transportation
- Starting in 1960s, some countries (Japan, India, S. Korea and China) recognized the economic benefit of supporting metal smelters leading to new or modernized facilities
- Metal commodity exchange warehouses led to stable but low metal prices. Margins became small leading to disincentives to modernized U.S. smelters to compete in global market
- U.S. government actively avoided supporting domestic metal production and instead pushed for the closure of "dirty, old smelters"



Dec. 1984

SUSTAINABLE SUPPLY OF STRATEGIC MINERALS

Challenge of ESG in Mining and Metallurgy

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- Concept – the digital mine for optimization, efficiency, safety
- Upstream –
  - Fuel switching from diesel – electrification coincides with drive to automate (both reduced emissions and improved safety metrics BUT impacts labor force)
  - Remote tech and automation as much as possible – drones and robotics for explosives, robotics for extraction and removal
  - Waste and water reduction to extent possible, improved tailings management (safety and public protection), capture residual minerals from waste, options for water resources (community interface)
- Midstream/downstream –
  - Improved logistics – emissions reductions across supply chains
  - Automation and digitization
  - Pressure on contractors (many mine operations are contracted) and vendors
- For companies of all types – measuring, reporting
- Un-level playing fields – across counties, investors
- It will take a long time.....

Challenge of Old Insecurities: The Problem of Fragile States

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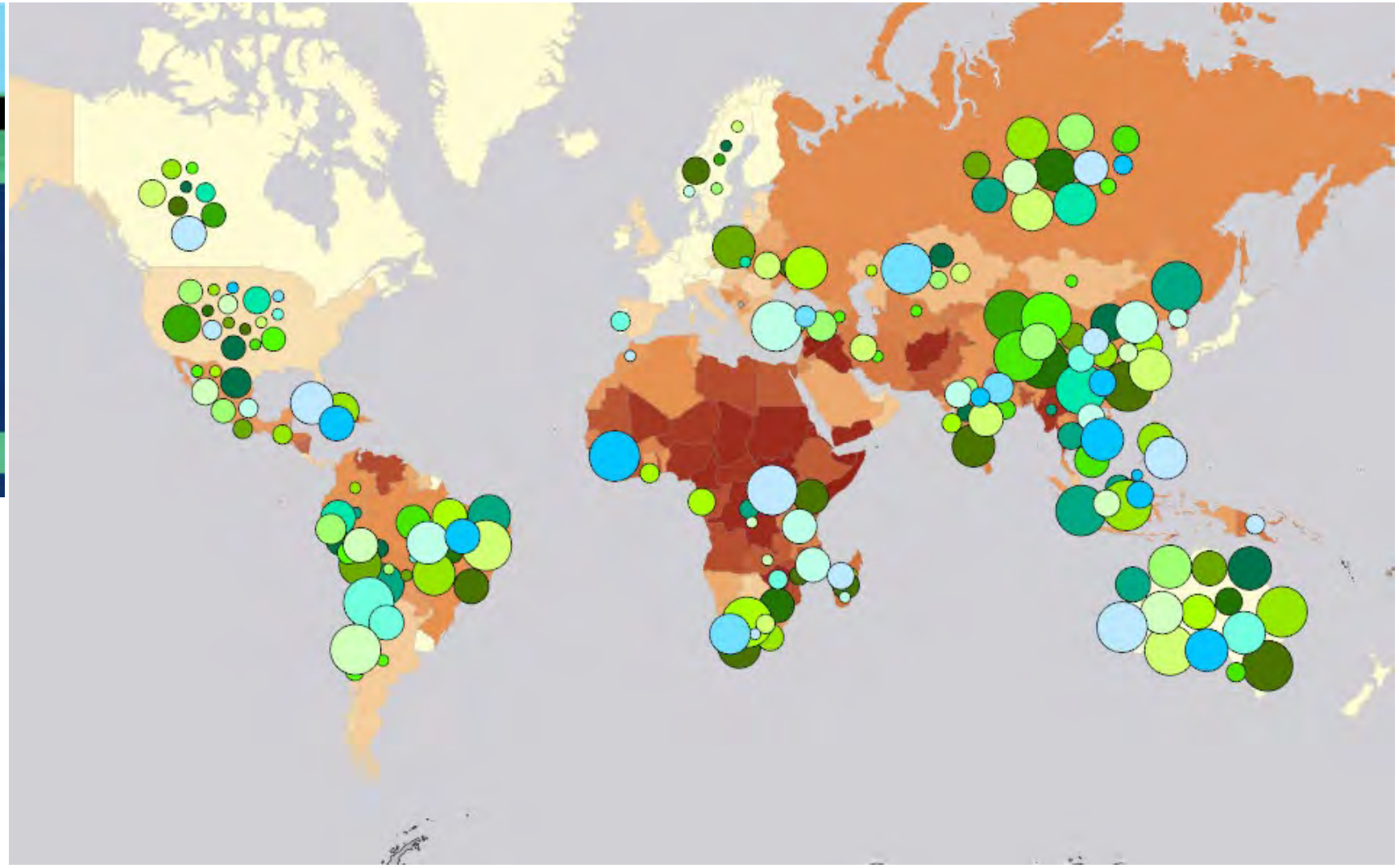

https://www.iisd.org/library/green-conflict-minerals-fuels-conflict-transition-low-carbon-economy

Work in Progress

Challenge of "Sustainability"

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Kern County, CA

Copper-colored lubricant is seen on an Acciona SA wind turbine. Photographer: Yael Markovitz/Bloomberg

Mud with contaminated rocks sit in front of a turbine taken in Photographer: Yael Markovitz/Bloomberg

Fragments of wind turbine blades await burial at the Casper Regional Landfill in Wyoming. *Photographer: Benjamin Rasmussen for Bloomberg Green*

Work in Progress

Regulatory Labyrinths

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Do ESG best practices help profitability OR does profitability help ESG best practices???

Work in Progress

Challenge of "Greenflation"

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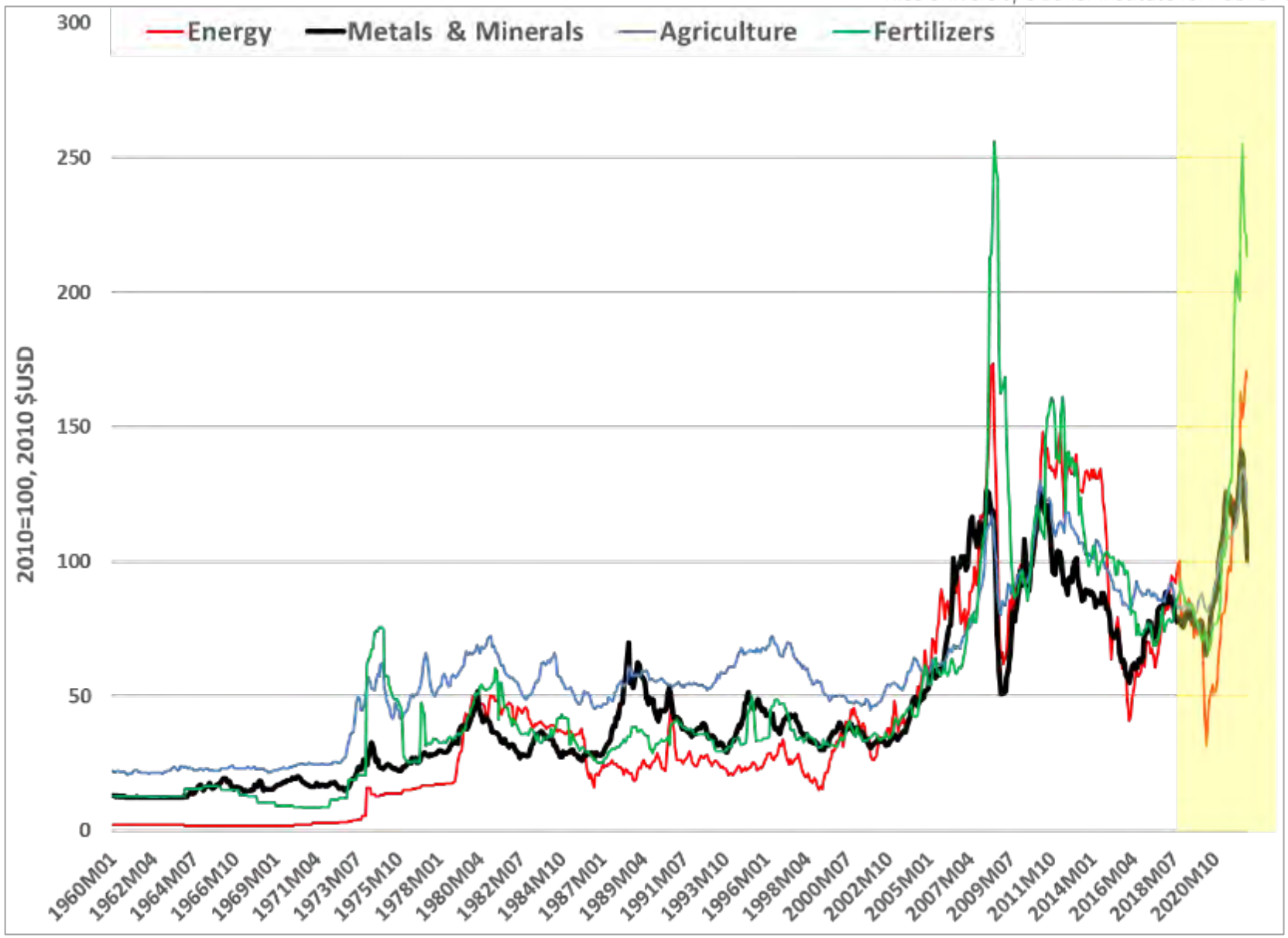

M. Michot Foss based on World Bank Pink Sheet

Can we recycle our way out of it?

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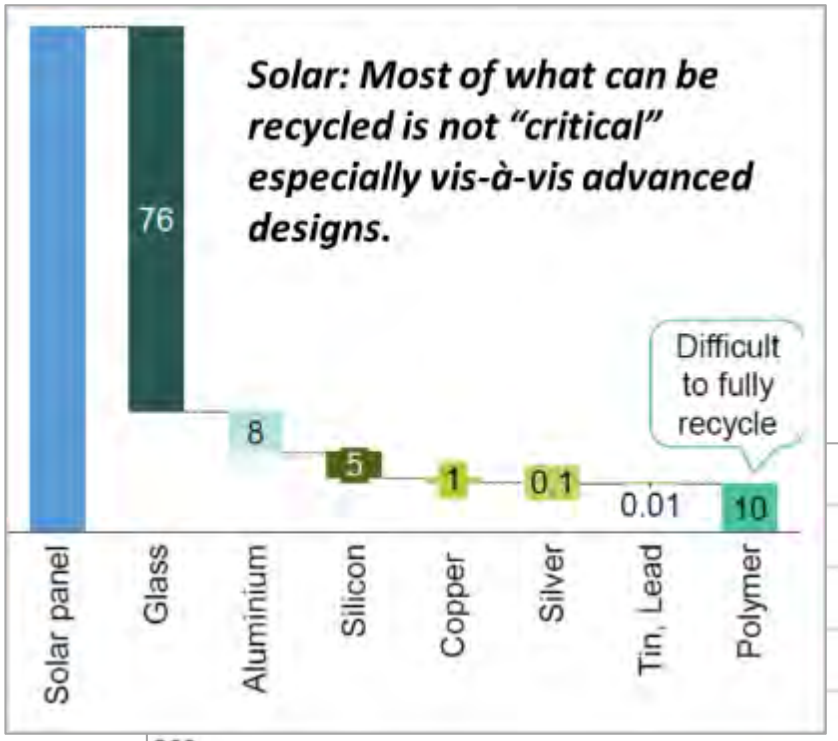
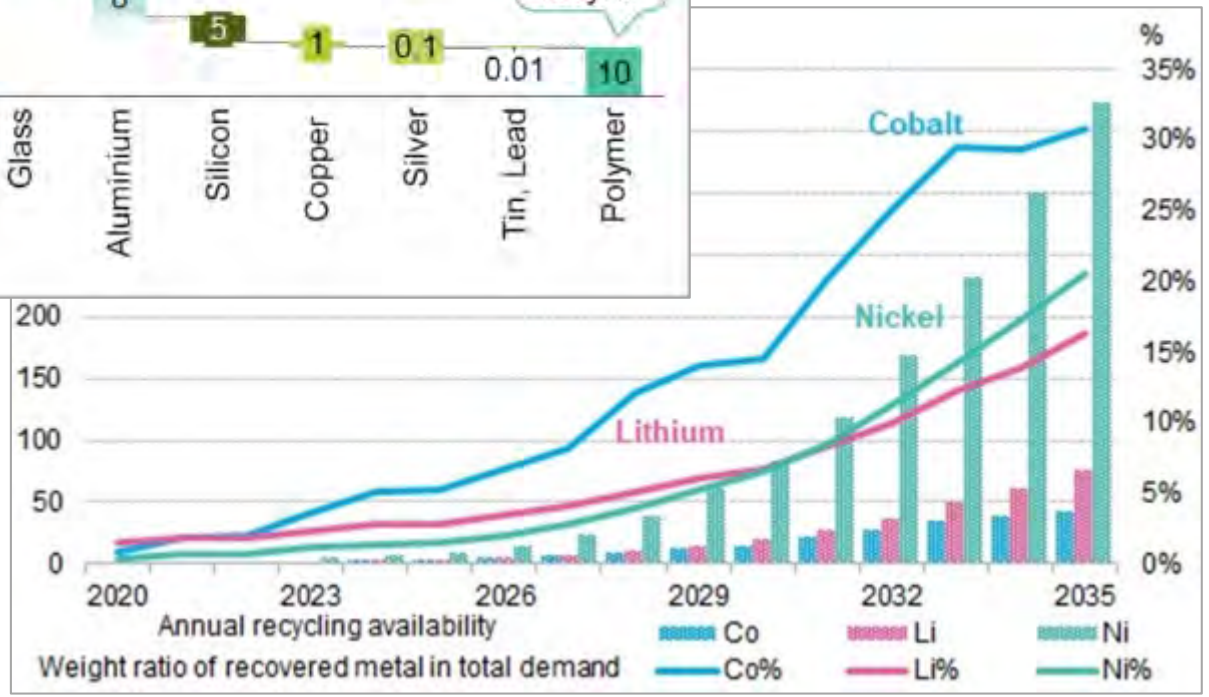
It's not like we don't recycle....

Commodity	U.S. Scrap Market Share
Iron & Steel	58%
Aluminum	53%
Copper	34%
Lead	71%
Zinc	25%
Nickel	52%





ISRI, EPA, Bernstein Research, BNEF (both used with permission)

Work in Progress

Can we substitute our way out of it?

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Scarce metal	Main application	Number of patents	Number of papers	Substitution level	Carbon nanomaterial substitute
Indium (In)	Transparent electrodes	18	>100	Material	G, CNT
Gallium (Ga)	Semiconductors	8	>100	Material	G, CNT
Beryllium (Be) and silver (Ag)	Conductive materials	6	>100	Material (Be) and elemental (Ag)	G, CNT
Antimony (Sb)	Flame retardants	5	>100	Material	G, CNT, F
Cobalt (Co), niobium (Nb) and tungsten (W)	Strong materials	5	>100	Material	G, CNT, F
Chromium (Cr)	Corrosion protection	3	>100	Material	G, CNT, F
Tantalum (Ta)	Capacitors	3	>100	Material	G, CNT
Tin (Sn)	Solders	2	22	Material	CNT
Germanium (Ge)	Optical fibers	0	2	Material	G, CNT
Platinum (Pt)	Catalytic converters	0	2	Element	G
Gold (Au)	Jewellery	0	0	–	–

https://www.sciencedirect.com/science/article/pii/S0959652617307564

Work in Progress

Can we explore our way out of it?

Frontiers: The Allure of the Oceans

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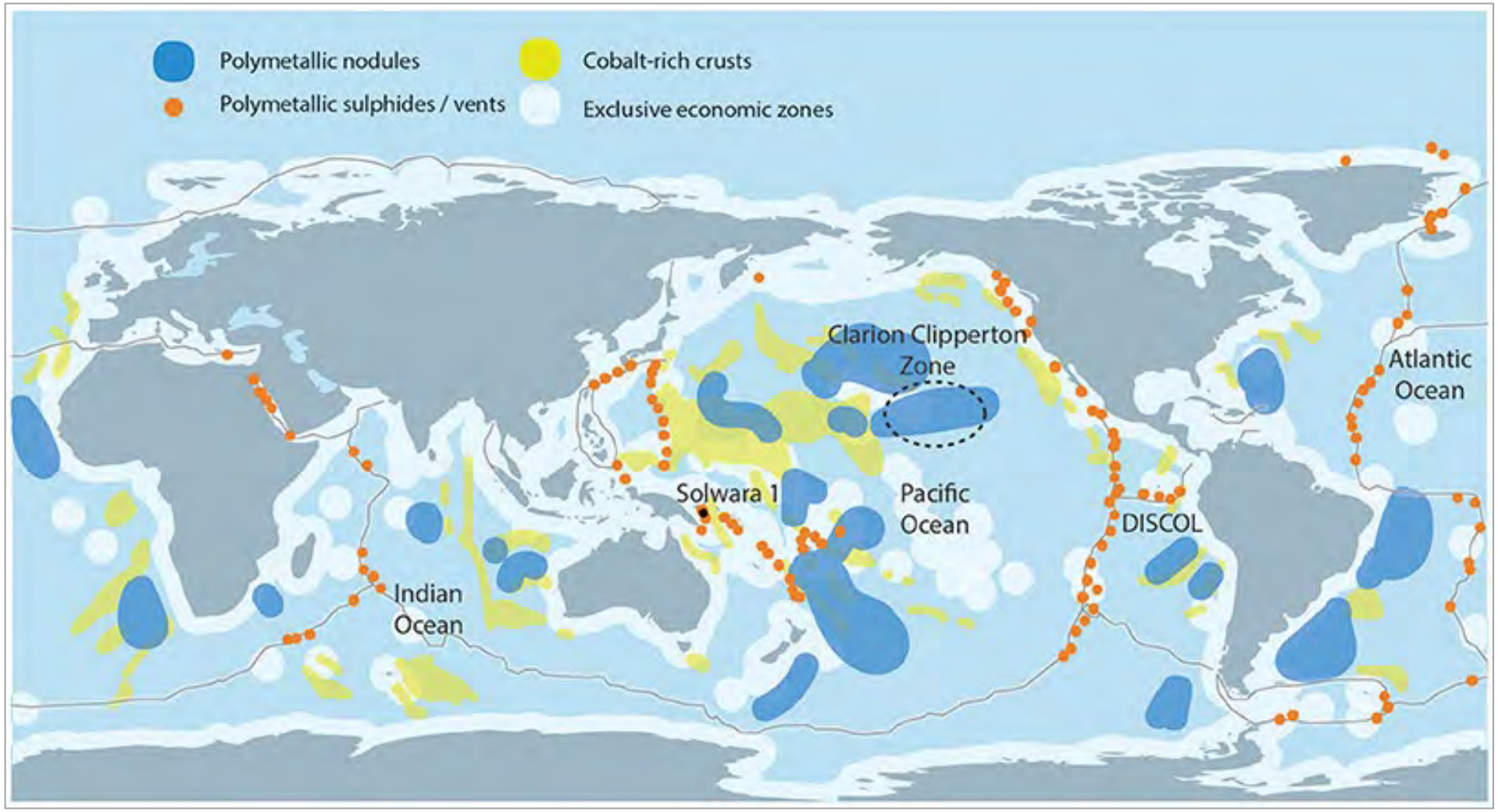

Miller et al., Front. Mar. Sci., 10 January 2018 | https://doi.org/10.3389/fmars.2017.00418

Can we explore our way out of it?

Frontiers: NOPE!

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NASA; Airbus/drone - https://www.rice.edu/jfk60

Conclusion: Putting Materials First

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- A strong rationale for slowing down, AND/OR doing something else
  - Questionable outcomes from green rushes – hidden costs, domino effects
- No alt energy incentives without materials forethought
  - Including semiconductors and other industrial policy targets
- Industrial policy means subsidies
  - Subsidizing incumbents creates barriers to invention and innovation
- Metals displacement, enhancement
  - Long history of "lightweighting" with plastics – train out of station
  - Carbon nanotube materials are alluring for performance – CNT alone or with metals doping for heavier duty products, desirable properties
    - But CNT challenges must be addressed head on
  - A potential way out of Chinese entanglements – but requires a complete "reset"

A Little Something Extra

Lagniappe

G20 Proposed Recommendation (Rice/Missouri S&T)

Critical Minerals/Materials Framework for Consideration

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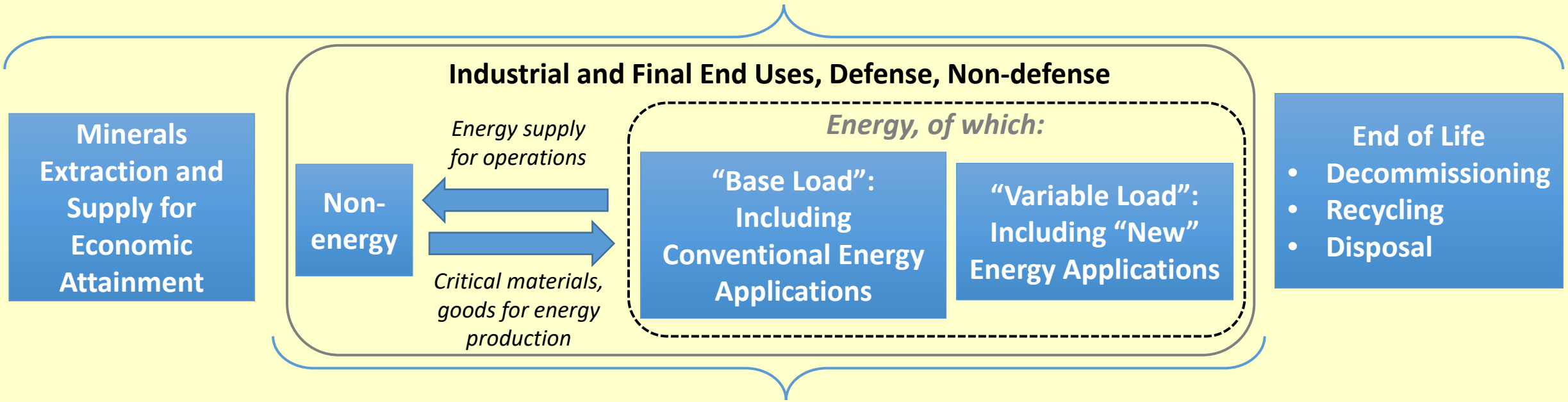
Contingencies: technology and applications, materials and materials inputs, global energy/minerals supply/deliverability security

Supply "push" effects include SSHE risks/uncertainties and life cycle management:
policy/regulatory architecture and development, standards, international coordination



Demand "pull" effects include: *commodity markets, fiscal/monetary, affordability*

SSHE = Safety, security, health, environment

Michot Foss, Moats, Awuah-Offei, https://www.g20-insights.org/policy_briefs/framing-energy-and-minerals-for-future-pathways/

World Mining Data Minerals Classification and Examples

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https://www.world-mining-data.info/

Iron and Ferro-Alloy Metals:

Iron, Chromium, ***Cobalt***, ***Manganese***, Molybdenum, ***Nickel***, Niobium, Tantalum, Titanium, Tungsten, Vanadium

Non-Ferrous Metals:

Aluminium, Antimony, Arsenic, Bauxite, Beryllium, Bismuth, Cadmium, ***Copper***, Gallium, Germanium, Indium, Lead, ***Lithium***, Mercury, Rare Earth Minerals, Rhenium, Selenium, Tellurium, Tin, Zinc

Precious Metals:

Gold, Platinum-Group Metals (Palladium, Platinum, Rhodium), Silver

Industrial Minerals:

Asbestos, Baryte, Bentonite, Boron Minerals, Diamond (Gem/Industrial), Diatomite, Feldspar, Fluorspar, ***Graphite***, Gypsum and Anhydrite, Kaolin (China-Clay), Magnesite, Perlite, ***Phosphate Rock*** (incl. Guano), Potash, Salt, Sulfur, Talc (incl. Steatite and Pyrophyllite), Vermiculite, Zircon

NOTE basics: Current commercial *Lithium*-ion battery types: LFP or LiFePo (*Iron, Phosphate*) and NMC or LiNiMnCo (*Nickel, Manganese, Cobalt*) with *Aluminium* *Graphite* electrode and *Copper* conductivity.

General Battery Concepts

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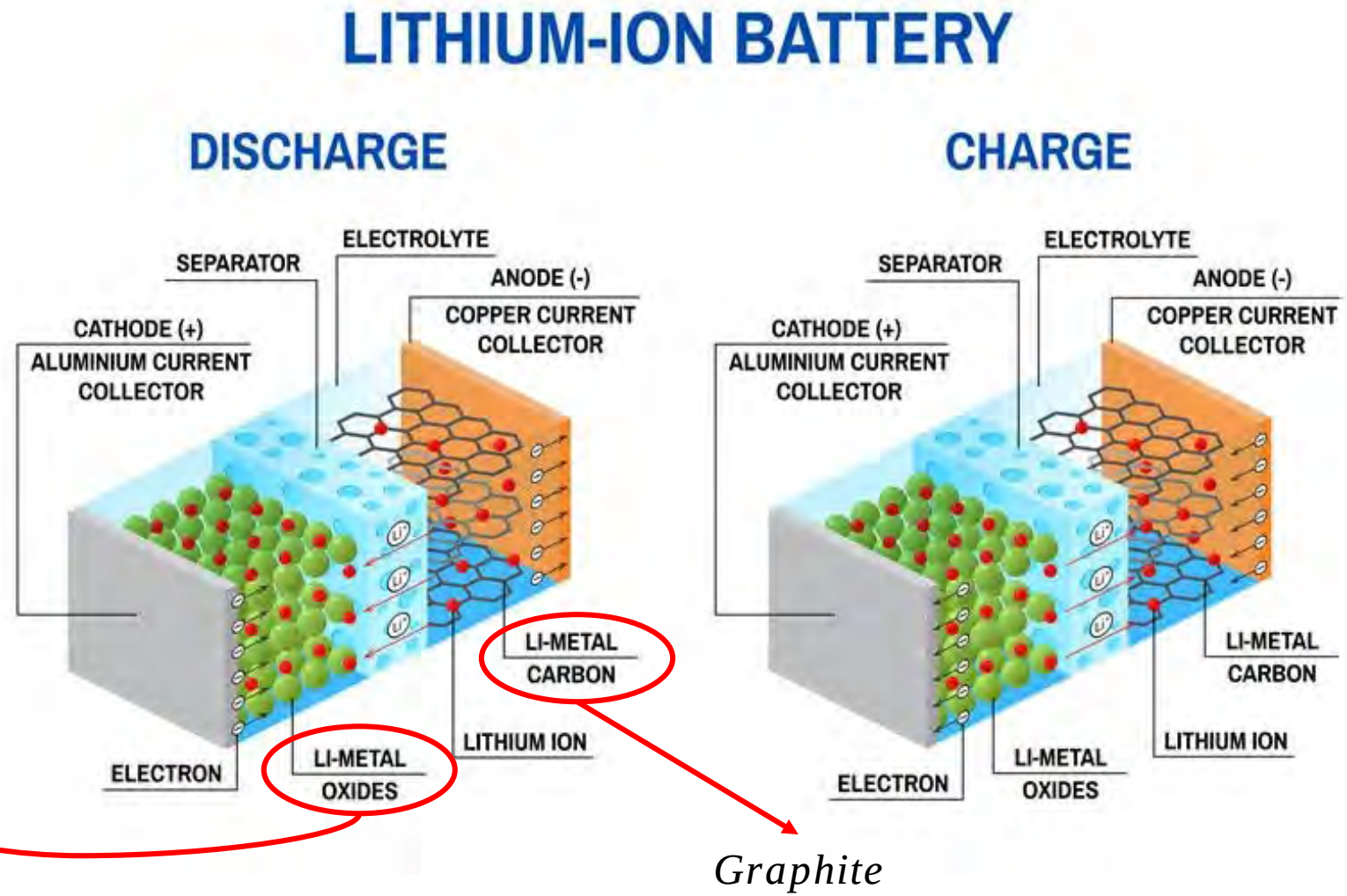

LFP – Iron, Phosphorous
NMC – Nickel, Manganese, Cobalt

Graphite

www.analyteguru.com/t5/Blog/Challenges-in-Lithium-ion-Battery-Manufacturing-and-Quality/ba-p/15961

Main Commercial Chemistries

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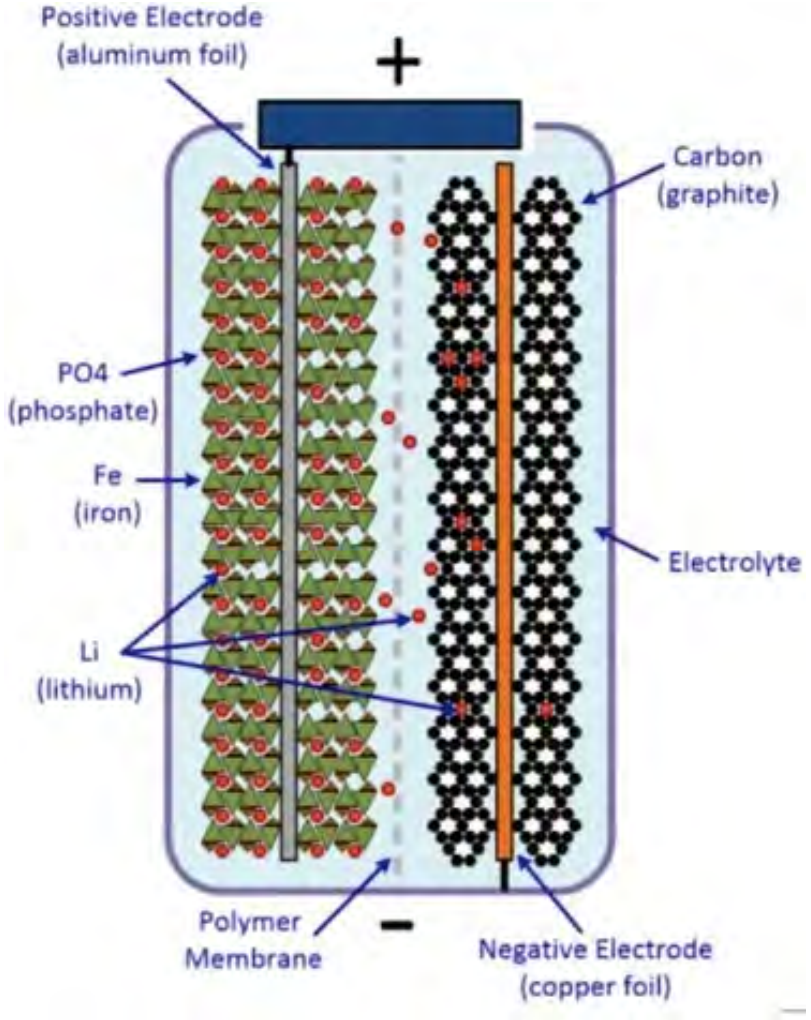
batteries-cost-versus-performance/

The Tesla LFP



batteries-teslas-new-choice-of-battery/

Highlighs of CES Nickel Case Study

center for ENERGY STUDIES
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- A Chinese gamble to seize premium pricing for laterites
- SME Thrive, September 22, 2022
- See Suggested Resources and Links

A Story About Quality

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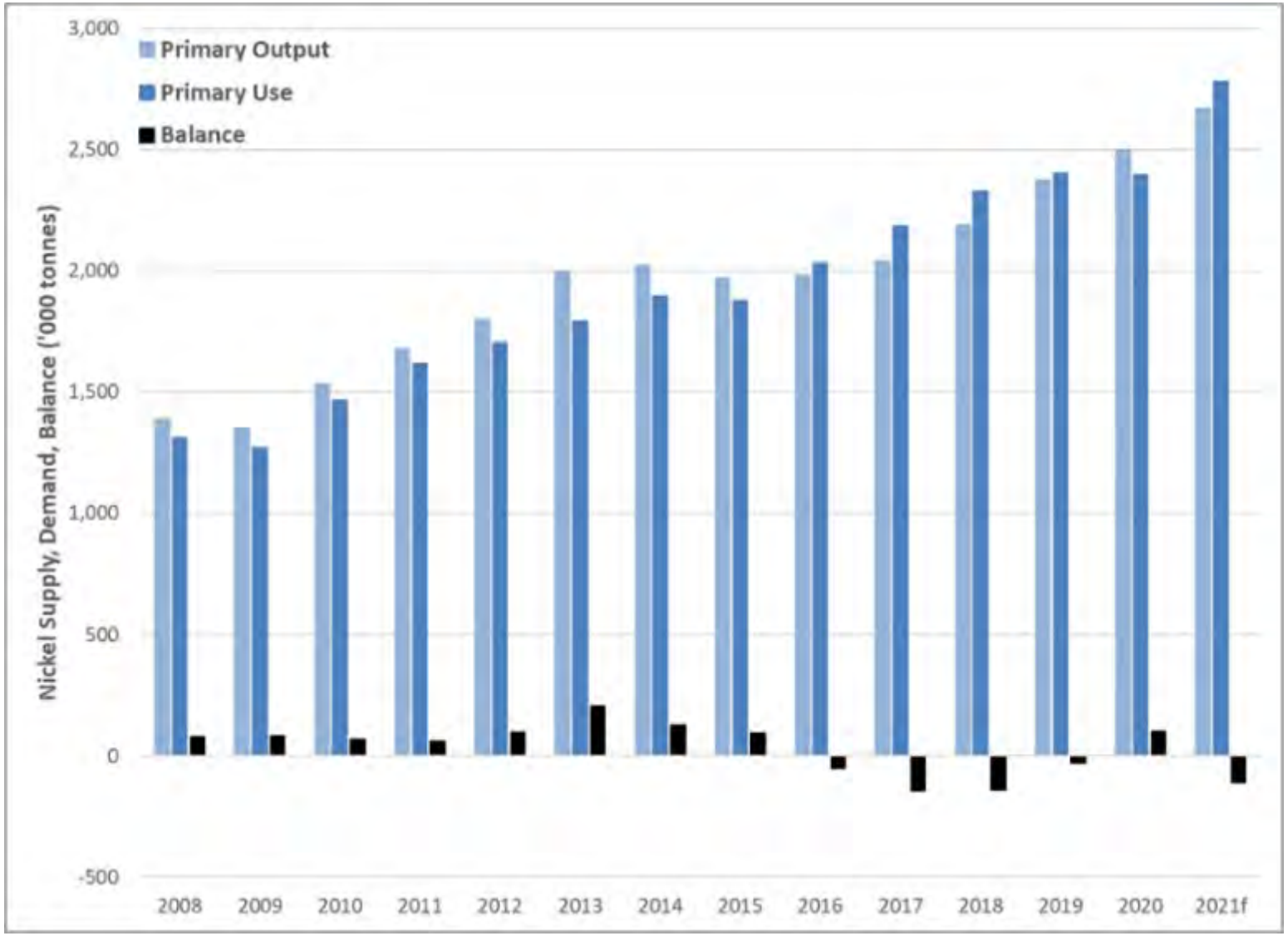
Historical Supply-Demand Balances



Nickel Institute

Global Recovery Rates and Production

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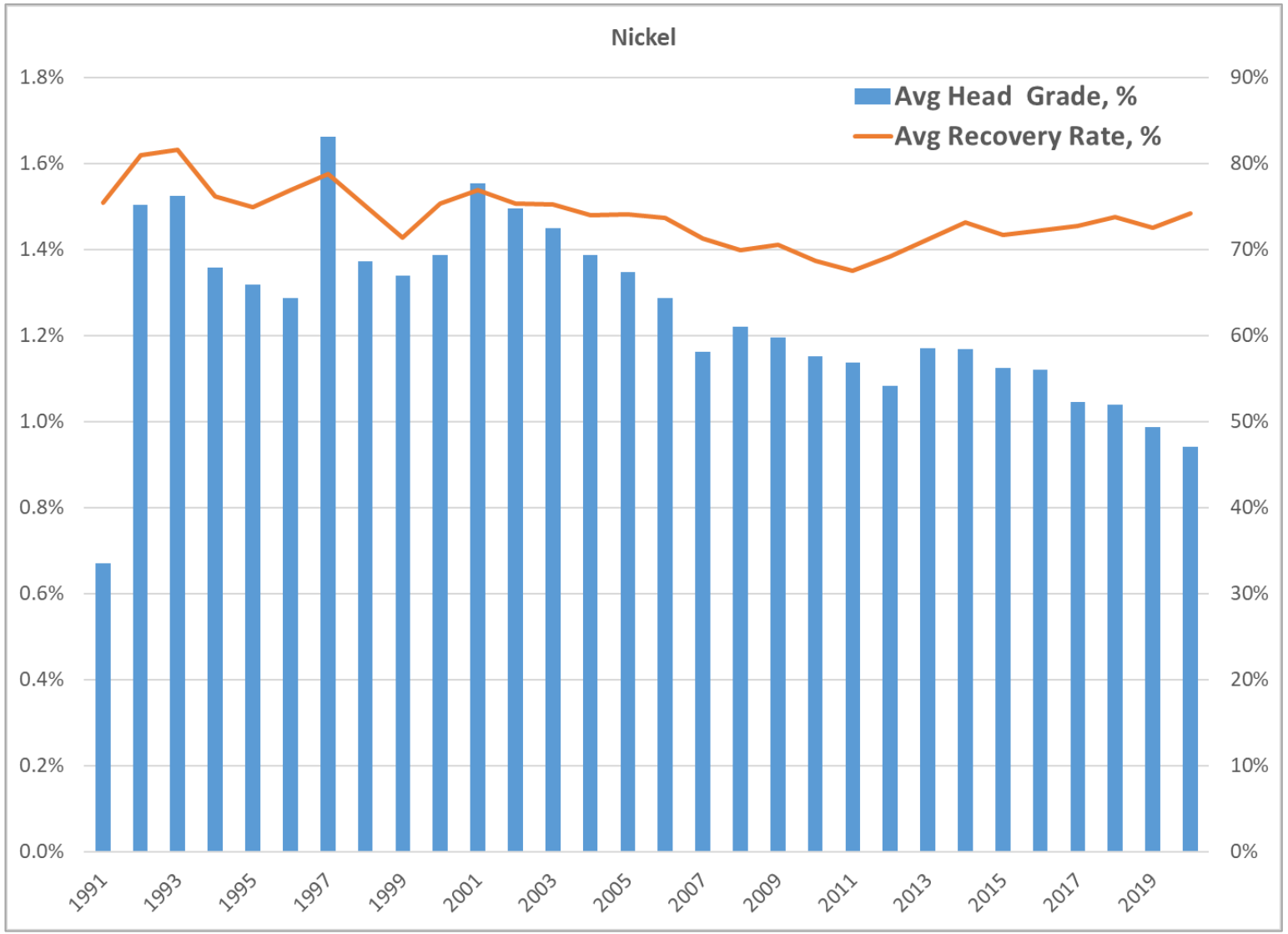
- Head grades reflect maturity across active properties, low rates of exploration, discovery.
- Improvements in head grade reflect periodic discoveries/new assets.
- Recovery rates can be improved through capex infusions in processing, recovery from tailings, etc.



Author analysis based on SPG, accessed via license.

Follow the Money

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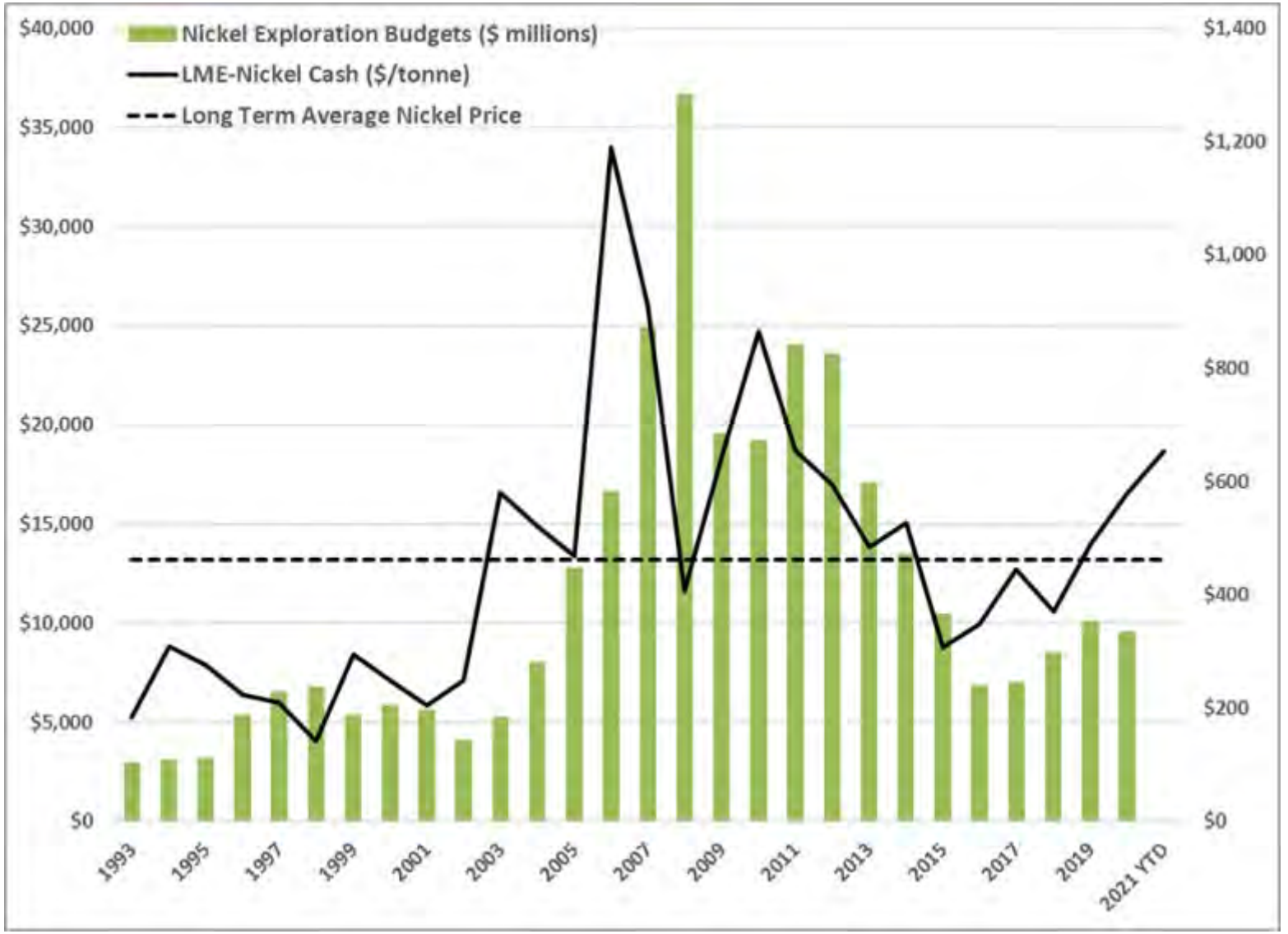
Exploration budgets follow risk-weighted expected returns, sensitive to price.



Author analysis based on SPG, accessed via license.

Historical Nickel Discoveries

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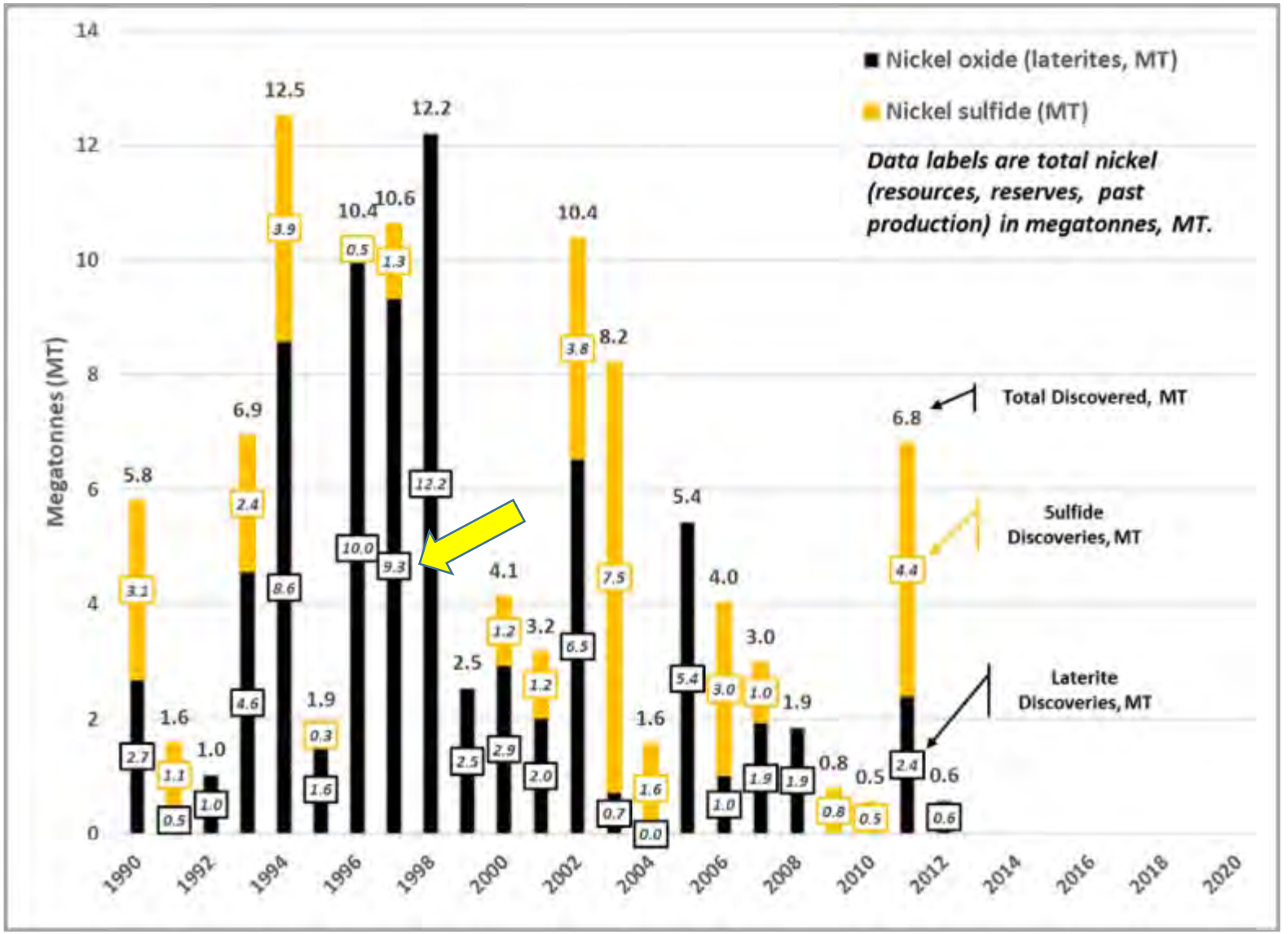
- No major discoveries since 2012.
- **Weda Bay**, with discovery confirmed in 1996 (reported in 1997, arrow) and an estimated 9.3 MT of producible reserves, serves as a good illustration of cycle time.
- From the point of discovery, which entailed prior years of drilling and testing, the property only entered operation in 2020, **some 25 years later**, with 0.0235 MT produced that year.



Author analysis based on SPG, accessed via license.

Work in Progress

Global Supply Curve

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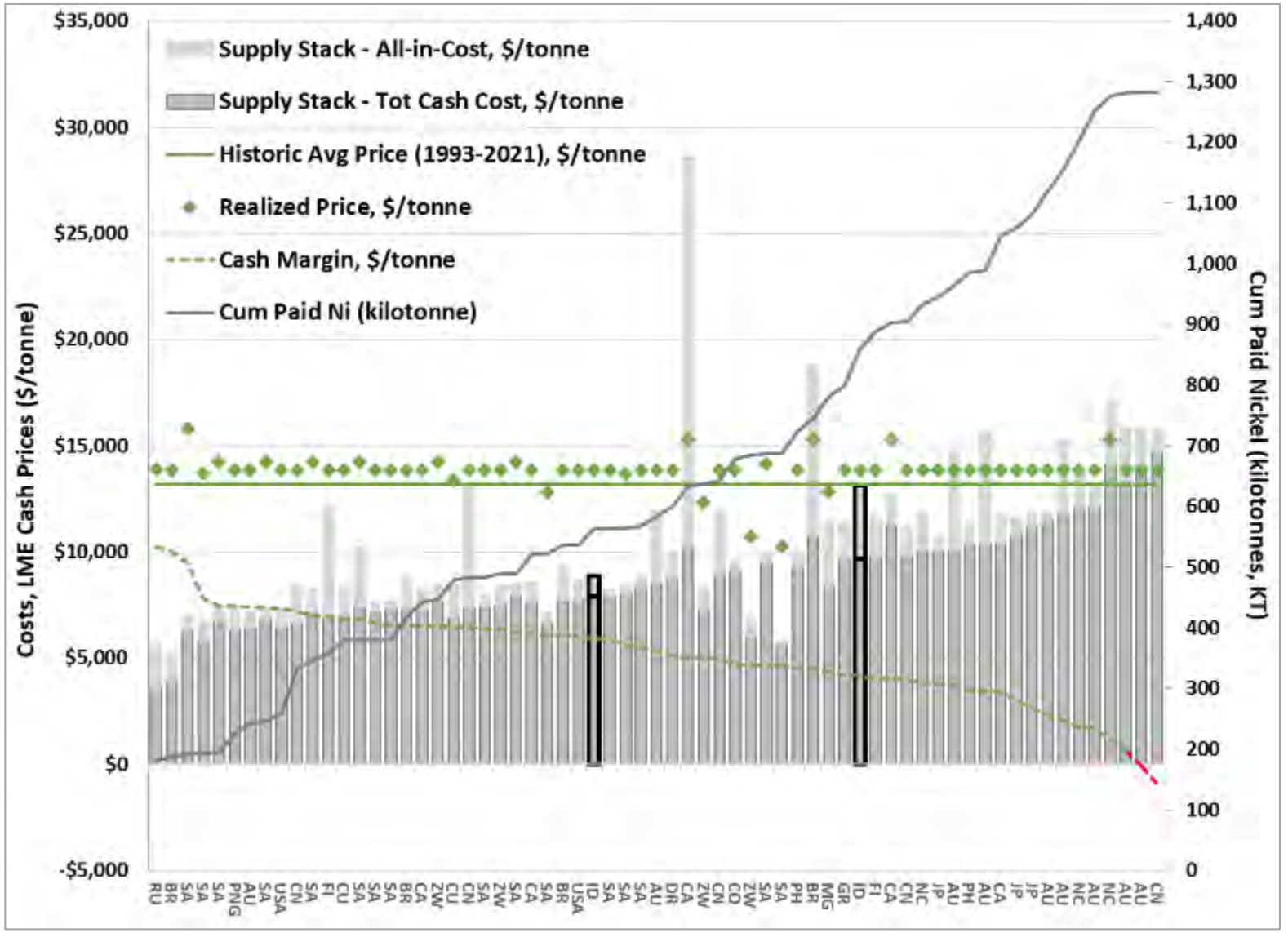
Cum paid metal, ranked by profitability.



Author analysis based on SPG, accessed via license.

Costs for Major Laterite Producers

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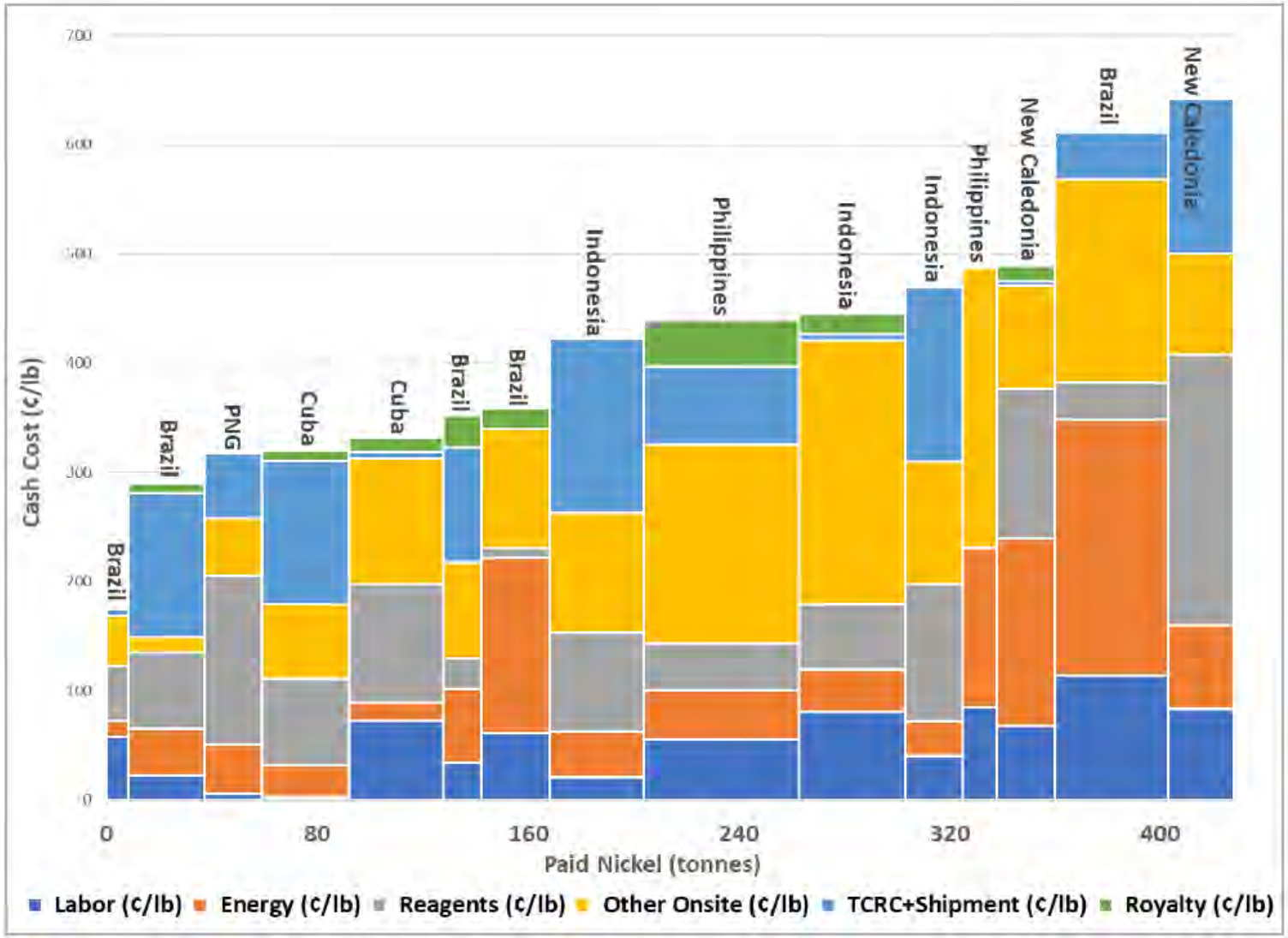

Indonesia Trade and Export Ban

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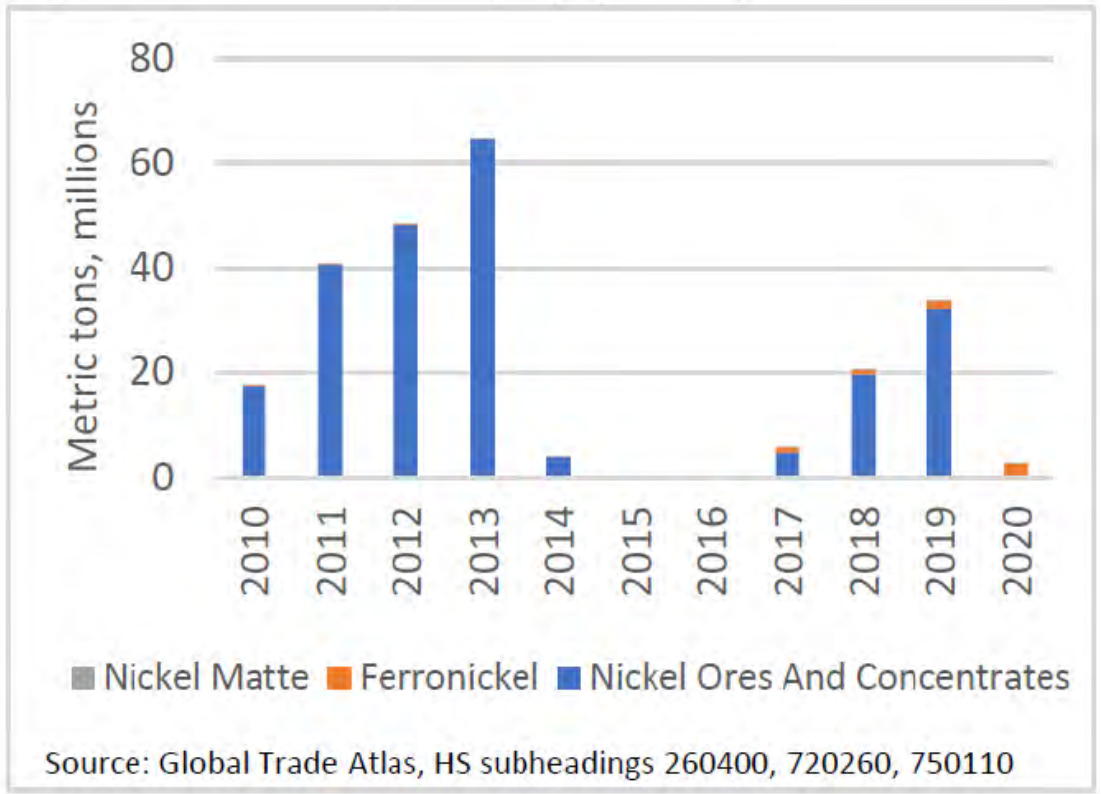

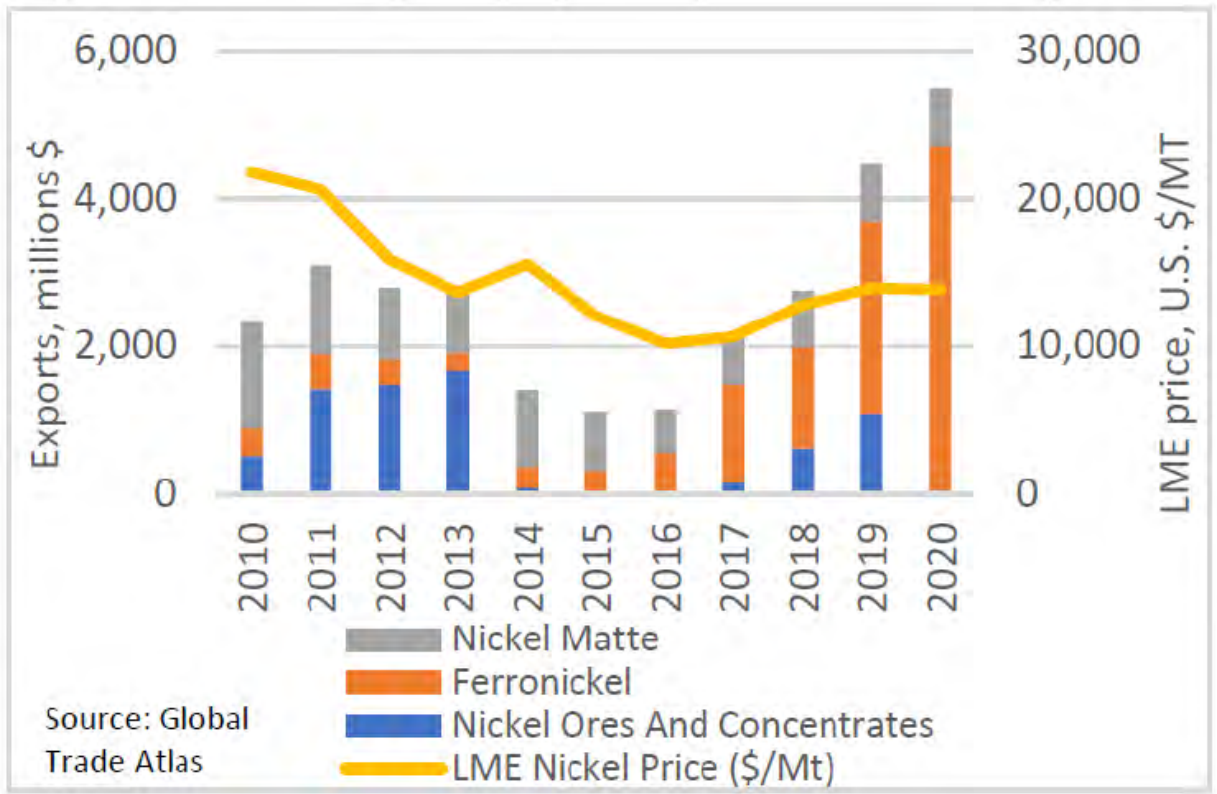

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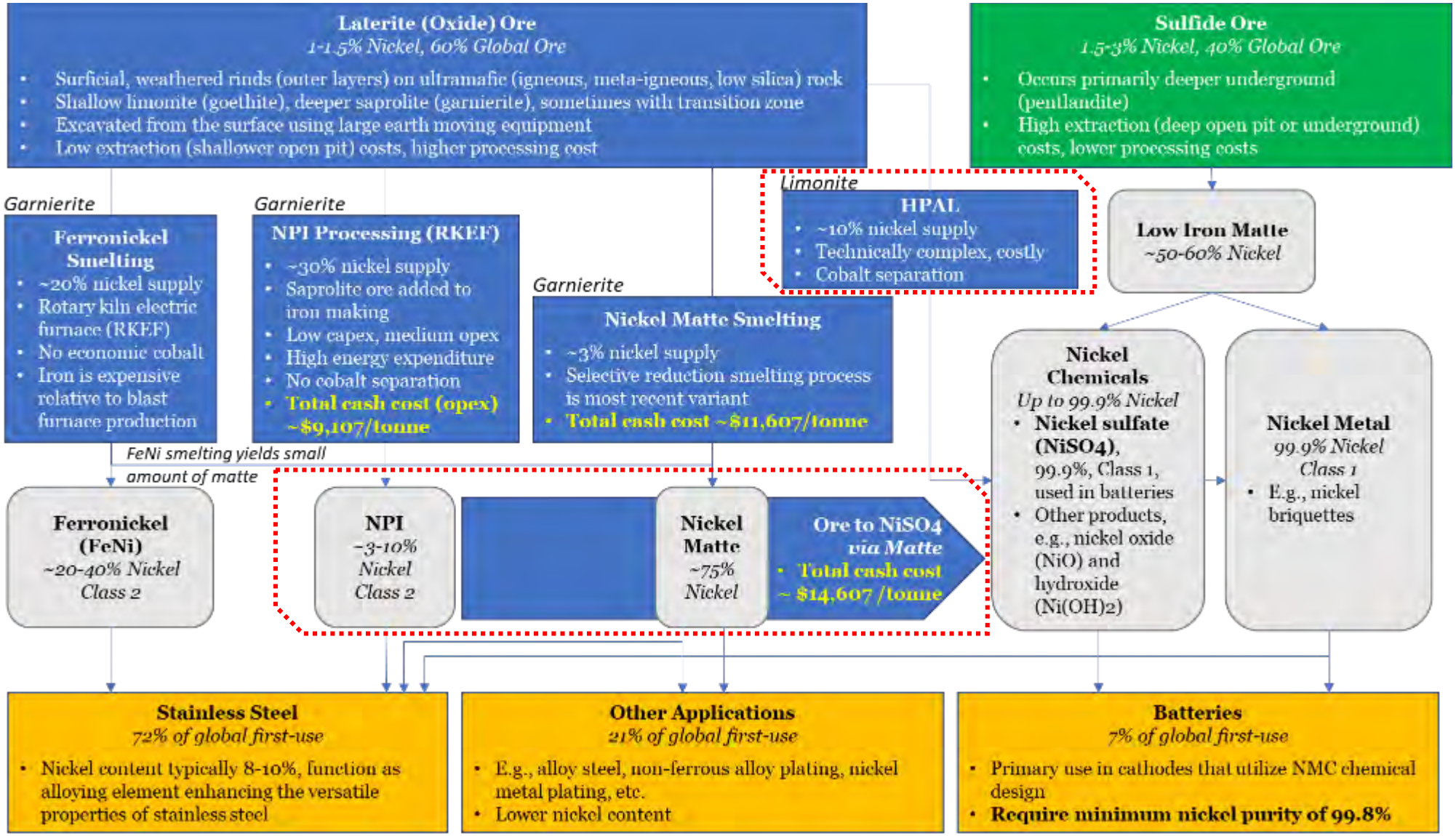
Generalized Nickel Processing Streams

Note that sulfide ores typically are crushed, ground, floated to achieve concentrate and flash smelted to matte.

Red-dashed boxes capture strategies to process low-grade lateritic ores to battery grade nickel.



Sources: Mineral nomenclature from USGS, see endnote 4. UBS Research, from https://www.kitco.com/commentaries/2018-09-13/Nickel-Laterite-s-Integral-Role-in-the-Coming-Nickel-Boom-Part-2.html. For ore treatment processes, please see Monhemius, A. J., 1987, Treatment of Laterite Ores of Nickel to Produce Ferronickel, Matte or Precipate, Imperial College, London, January, https://www.researchgate.net/publication/291165654_Treatment_of_laterite_ores_of_nickel_to_produce_ferronickel_matte_or_precipitated_sulphide and Davenport, W. and Moats, M., 2014, Nickel and Cobalt Production, Treatise on Process Metallurgy: Industrial Processes, https://mail.google.com/mail/u/0/?tab=rm#inbox/FMfcgzGllVqqdbQTprVMRmTWrpNSRjfp?projector=1&messagePartId=0.4. For processing costs, please see Sappor, J., 2021, Commodity Monthly – Nickel April 2021, S&P Global Market Intelligence, April, accessed via license. For global first-use figures, please see Nickel Institute, 2021, About Nickel and Its Applications, https://nickelinstitute.org/about-nickel-and-its-applications/.

Processing Costs, Cash Margins

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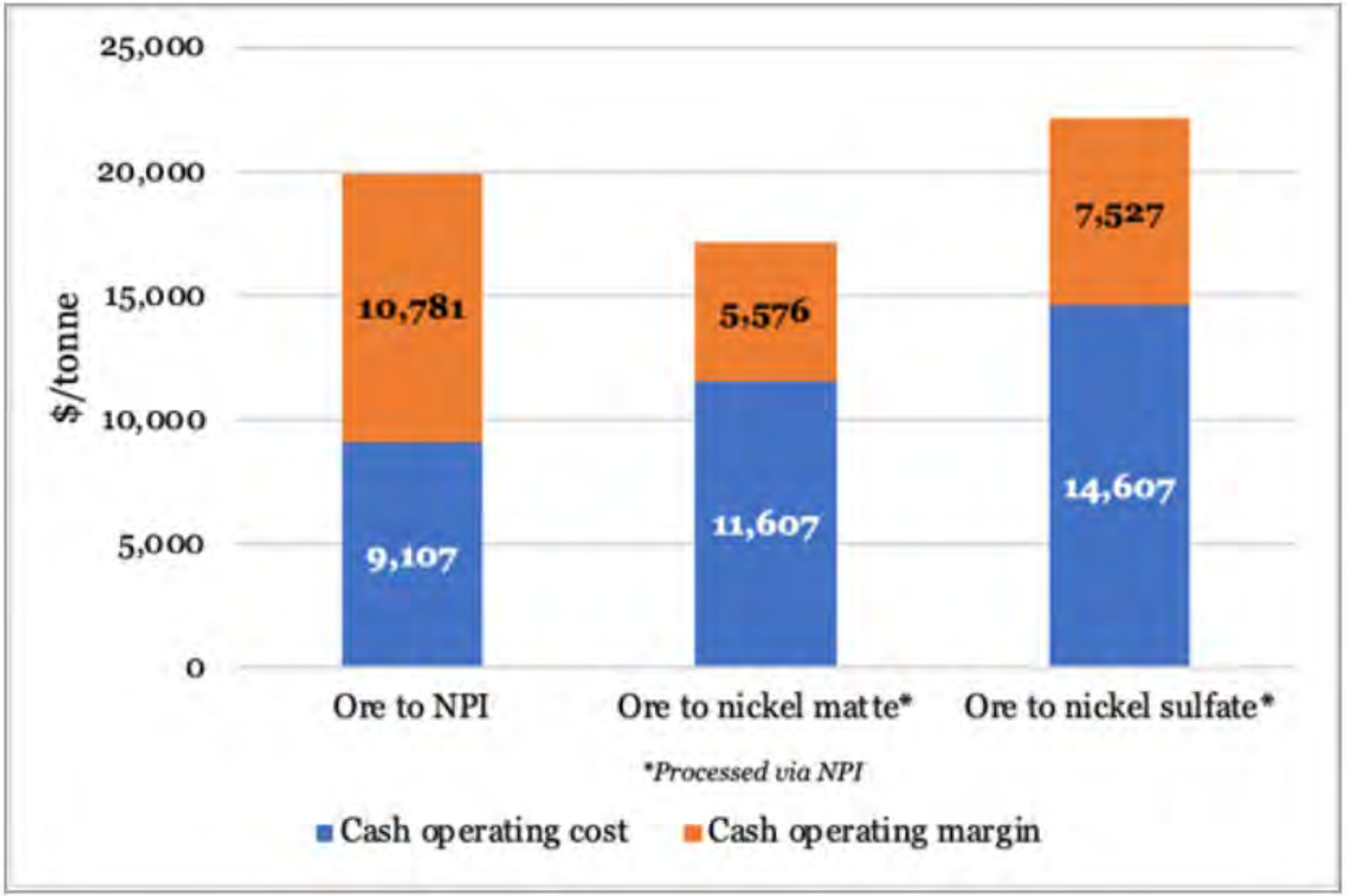

The Challenge of Waste

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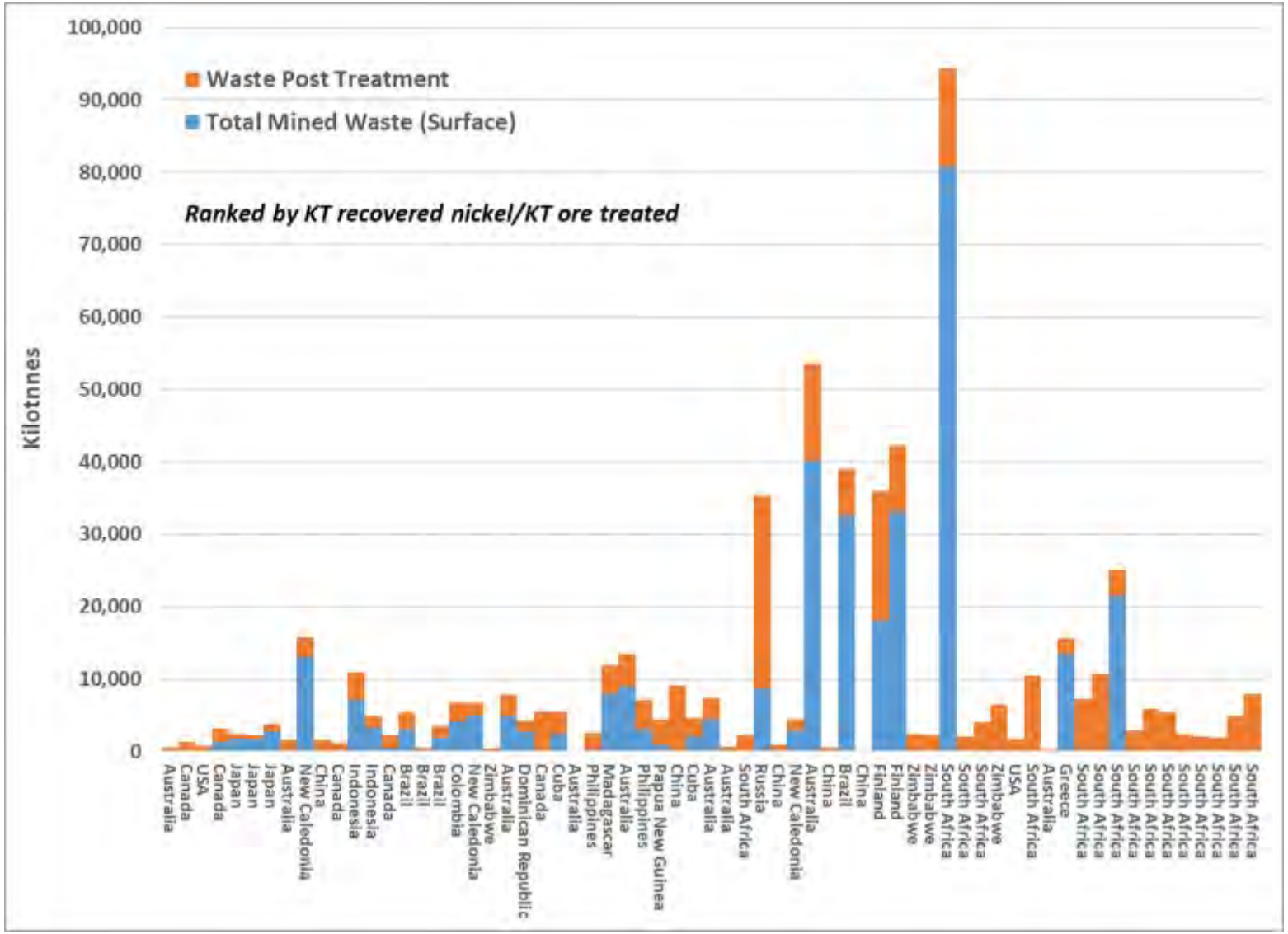

Closer Look at Trading Adventures

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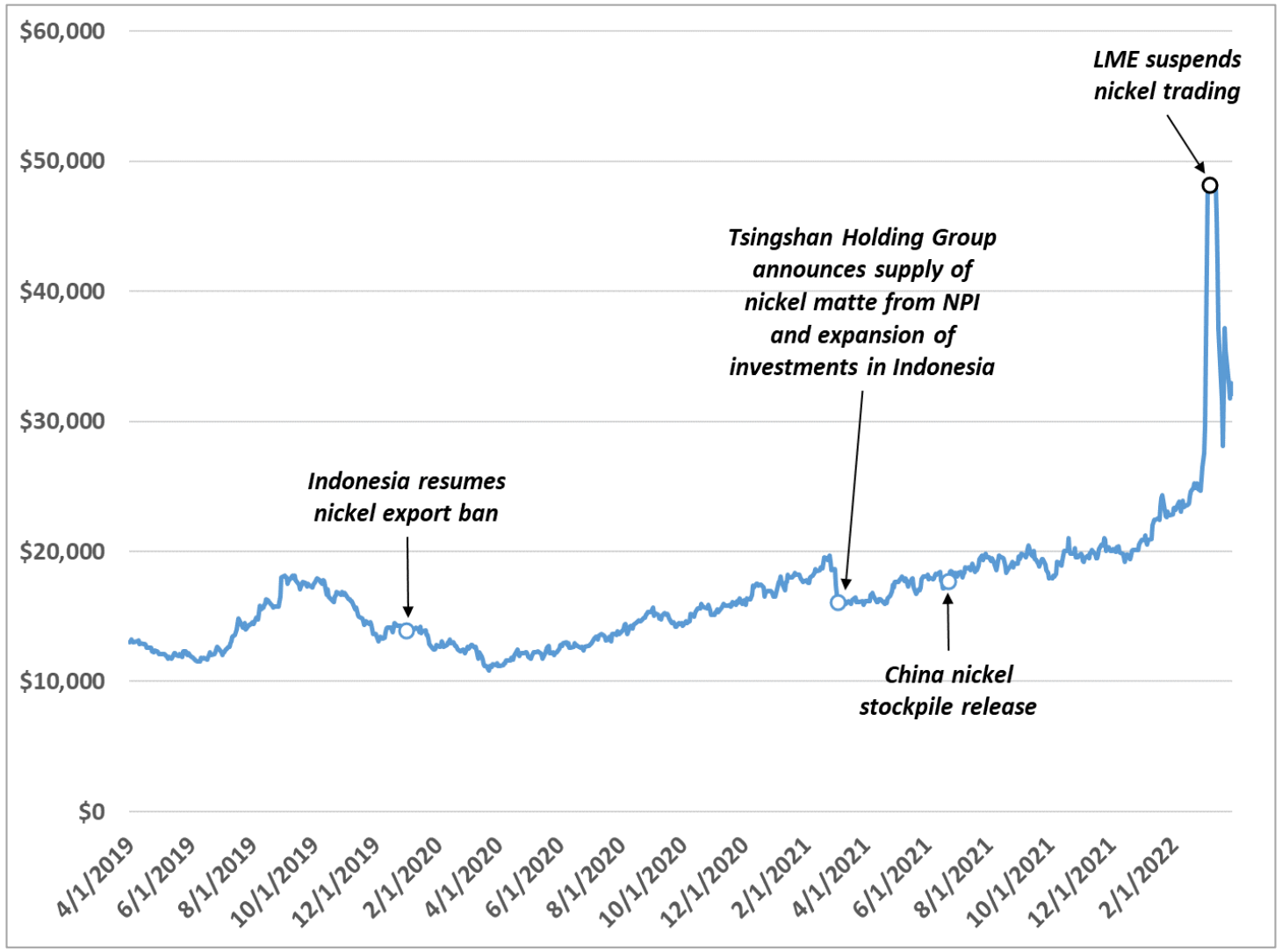

Geopolitics for Everyone

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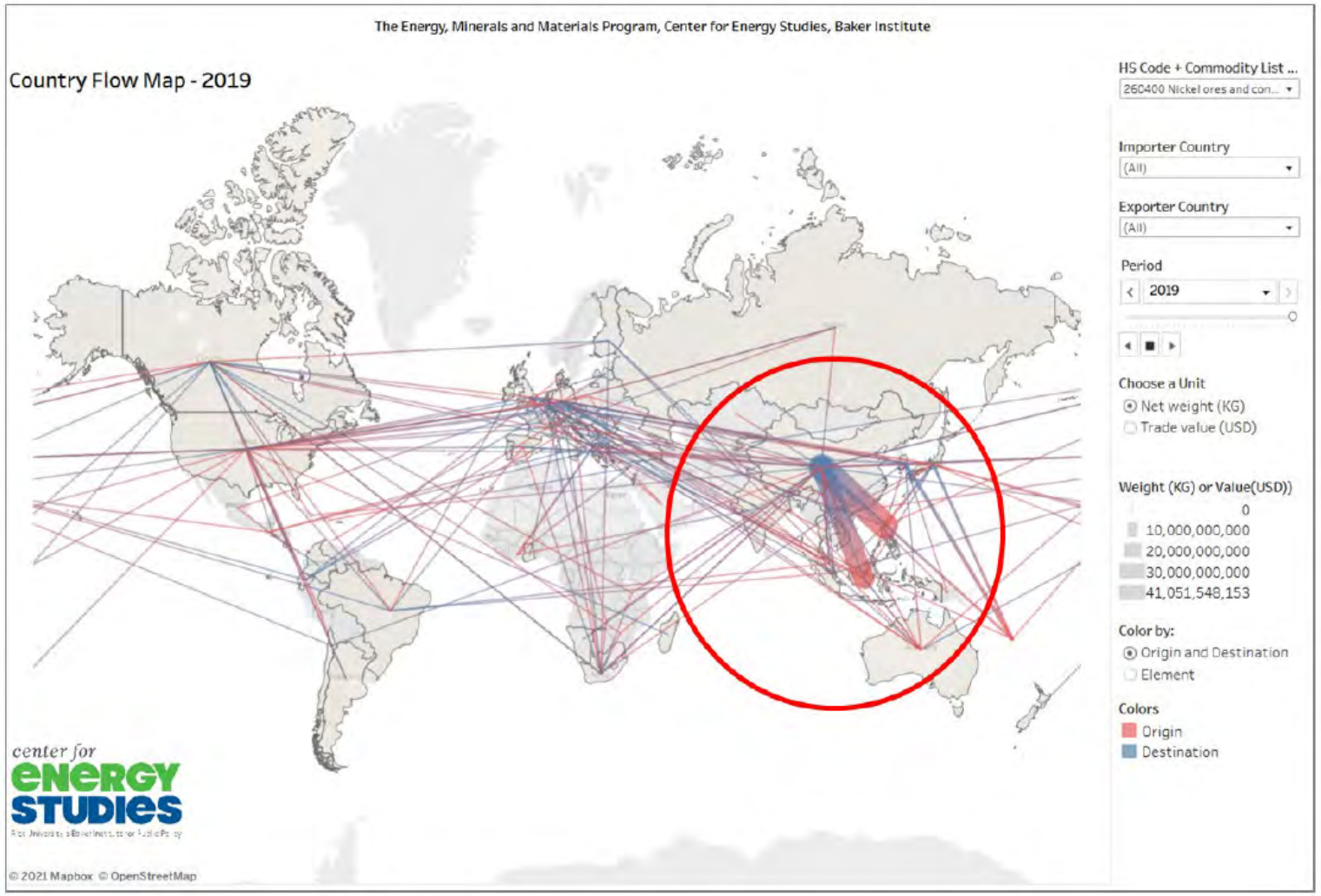

Suggested Resources and Links

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Rice University's Baker Institute for Public Policy

- M. Michot Foss, Future Minerals Heartland, Future Minerals Forum 23, Riyadh, Saudi Arabia
- M. Michot Foss, J. Koelsch, China's Rare Earths Dominance
- M. Michot Foss, J. Koelsch, What China's control of nickel means for the energy transition
- CES China Energy Map https://www.bakerinstitute.org/chinas-energy-infrastructure/
- CES minerals production/trade visualizations https://www.bakerinstitute.org/energy-minerals/
- M. Michot Foss, testimony before the U.S. Senate Committee on Energy & Natural Resources, March 10, 2022,.
- M. Michot Foss, testimony before the U.S. House Subcommittee on Energy on the CLEAN Future Act, May 5, 2021
- M. Michot Foss, recommendations to the Biden Administration
- M. Michot Foss, M. Moats, K. Awuah-Offei, G20 technical brief on future minerals pathways
- R.A. Meidl, M. Michot Foss, J. Li, forthcoming, A Call to Action for Recycling and Waste Management Across the Alternative Energy Supply Chains
- R.A. Meidl, recommendations to the Biden Administration Waste Management and the Energy Transition
- R.A. Meidl, Measuring the True Cost of Sustainability: A Case Study in a Green Energy Approach
- R.A, Meidl, Smart policy and innovative technologies, like advanced recycling, will deliver on climate and sustainability goals
- G. Collins and A. Erikson, China's Climate Cooperation Smokescreen, U.S.-China Competition Enters the Decade of Maximum Danger
- G. Collins and M. Michot Foss, Want to Derail the Energy Transition? Take Fossil Fuels Out of the Mix, Energy Transition Valley of Death