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Testimony

Testimony to the US House Committee on Energy and Commerce

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This testimony was delivered at the U.S. House Energy and Commerce Hearing on "Securing America's Critical Materials Supply Chains and Economic Leadership" on June 13, 2024.

Summary

Energy transitions are complex and will vary hugely across regions and countries. Supply chains matter. ***Energy transitions require materials transitions***. Sustainability is multi-faceted. Innovation and growth will shape the future of energy (and economies). The main questions for minerals and materials supply chains are these.

- How will supply chain realities play out across competing end uses? With what tensions between and among producers and consumers?
- As pressures to demonstrate sustainability — broadly defined — continue to unfold, how will these impinge on ability of the extractives industries to respond to demand signals?
- What will be the effect of ever more complicated geopolitical and trade alignments?
- How will budget constraints ultimately dictate what businesses and governments can reasonably do?
- ***And finally, what could <u>materials transitions</u> for energy transitions even look like?***

The minerals and mining industries face challenges that are definitive with respect to supply chains. It is our belief that these challenges need better understanding in order to craft and implement appropriate responses, much less to be strategic. ***The grand challenges are: Minerals occurrences, commercialization, maturing assets, project cycle times, China's dominance, competitiveness (a U.S. dilemma), sustainability, markets, and old and new insecurities.*** There will be success cases for mining, minerals, and materials and potential breakthroughs. The path will be much longer and more arduous than typically presented to public audiences. ***Much of the political debate around materials challenges is embedded in conventional wisdom that use of fossil fuels must end.*** "Ending fossil fuels" affects deliverability of materials from hydrocarbons value chains, along with much else, not least national and economic security and resilience.

Many ideas exist for how to innovate in minerals and metals extraction. "In situ" mining has long been held out as a possibility for fuels (uranium and oil shale) and even essential metals. Capturing remaining products embedded in mined waste is a high and

increasing priority but bears many technical and environmental considerations. Mining and processing are targets for digitization and automation. ***Technology does not alter underlying geology, but it can stretch the boundaries for commercial recoverability.*** For the ultimate geology game changer, frontiers — the oceans, space? — attract plenty of imagination. Recycling is held up as a key solution for minerals and metals and most views are that we cannot pursue metals-dependent energy futures without it. ***Recycling is an industrial activity that entails its own requirements and bears its own sustainability tradeoffs.***

Could we leapfrog challenges in metals with advanced materials? Carbon-based materials predominate across sectors, segments, and end use applications. We have swapped plastics for metals for decades to reduce weight and cost and improve performance. Carbon nanotube fiber, CNTF, could unlock new options for applications that require electrical and thermal conductivity *and* tensile strength, for all of which CNTF excels. ***In all, governments should place materials first for policy making before attempting to pick technology "winners."***

Full Statement

Chairs Rodgers and Carter, Members of the Committee, thank you for inviting me to participate on this panel to provide input on the state of play regarding minerals and materials supply chains. My comments are drawn from a forthcoming report, ***Minerals and Materials Challenges for Our Energy Future(s)***. Our report focus is consistent with the core principles established for CES[1] — that energy transitions are complex and will vary hugely across regions and countries, that supply chains matter, ***that energy transitions require materials transitions***, that sustainability is multi-faceted, and that innovation and growth will shape the future of energy (and economies). The main questions for minerals and materials supply chains are these.

- How will supply chain realities play out across competing end uses? With what tensions between and among producers and consumers?
- As pressures to demonstrate sustainability — broadly defined — continue to unfold, how will these impinge on ability of the extractives industries to respond to demand signals?
- What will be the effect of ever more complicated geopolitical and trade alignments?
- How will budget constraints ultimately dictate what businesses and governments can reasonably do?
- ***And finally, what could materials transitions for energy transitions even look like?***

As we finalize our report, the U.S. has taken a discernible shift toward "industrial policy" with "energy transition" and related manufacturing investment. A pertinent question is whether proponents truly are serious: ***Will policy makers really do whatever it takes to***

boost supply chains and the basic industries essential for making it all happen, including or even especially at home? Across the minerals and materials landscape, producers expect more robust demand and considerable price appreciation associated with these policies. The massive commitments of public, taxpayer dollars to "de-risk" green energy tech and key inputs like semiconductors along with other goods carry with them promises of domestic content, jobs, and economic development.

The minerals and mining industries face challenges that are definitive with respect to supply chains. Even without industrial policy and energy transition stimulus these challenges would, at some point, influence the delivery and cost of metals for key end use markets and applications. It is our belief that these challenges need better understanding in order to craft and implement appropriate responses, much less to be strategic.

- **Minerals Occurrences:** The global domain is rich in periodic table elements, but ***these do not occur in mineral form in equivalent abundance or equivalent quality.*** The earth's mineral estate is, of course, overlain by political boundaries and trade patterns that cannot be ignored.
- **Commercialization:** The wide variabilities in concentration and purity bear inferences for commercialization. ***These wide variabilities dictate — as they always have — whether ventures can meet economic targets.*** Commercialization is further complicated by demand for co-products of major metals with complex interactions as needs evolve for elements crucial to advanced technologies and materials.
- **Maturity of Assets:** Mines are built to last decades or more. Yet, a particular concern is the age of the current mining and minerals processing fleet (Figure 1). Ore grades decline as mining progresses which means increased operating costs. ***The ageing of the worldwide mining asset base also is an artifact of the difficulty in achieving new investment and new projects.*** Older facilities are less favorable for "upgrades" (although experiments are underway to capture incremental supply and key byproducts from mined waste) and investment in "ESG" projects (environment, social, governance). Maturity of assets also raises the question of replacement, adding to the burden on supply curves.
- **Project Cycle Times:** If attention has been galvanized by anything when it comes to ambitions for minerals and metals and status of the mining industry it is the length of time that it takes to reach "paid metal" from new investment (Figure 2). ***An uncomfortable fact is that already long cycle times appear to be getting longer.*** Long cycle times underlie a distinct feature of global minerals supply chains today, the very unlevel playing field that exists with respect to who controls supply and thus exerts ultimate influence on markets and economies.
- **China's Dominant Market Shares:** China is both materials supplier and factory to the world, a result of that country's astounding industrialization, the domestic base needed to support manufacturing, and a surge in outbound investment as China's raw materials needs outstripped its own ability to supply them (Figure 3).

While the accomplishments of Chinese industry and businesses are substantial and contribute to prosperity for both Chinese citizens and the world at large, ***heightened trade and security conflicts in the "new minerals world order" threaten to upend established views on energy and environment and even the post-World War II established order.***

- **Competitiveness:** The evident problem in view of the "new minerals world order" is whether the U.S. and other major Western economies can regain "mojo" in mining and minerals processing to support their domestic initiatives (Table 1). ***When it comes to mining and processing competitiveness in the U.S., the slide since the mid-1980s has been long and hard.*** It is worth considering whether heft in the U.S. oil and gas industries and how to deploy those existing footprints in new and creative ways might be a better boost to domestic competitiveness.
- **Sustainability in the Mining Industry:** Ideas about shifting away from fossil fuels to metals-centric alternative energy technologies ("alt energy tech") come with heightened scrutiny of metals and minerals supply and value chains. In countries with established regulatory oversight, a level of confidence can exist that mining operations achieved permissions based on sound planning and engineering. Confidence can extend to mining operations that are consistently in compliance. Regulatory requirements and devotion to safety once defined sustainability. No more. ***The embrace of "green" energy and "green" materials has meant the embrace of "just and affordable" energy futures — not least because taxpayers must provide the essential backing.*** Whether truly green materials can be provided and be affordable while satisfying the gamut of views and expectations regarding environmental justice is, by itself, a massive undertaking. All of this is compounded by the maturing global mining fleet and the legacy of abandoned mines and facilities.
- **Markets**: Metals have been priced and traded in formal markets over a much longer history than oil. ***Metals trading remains far smaller even though growth has exploded during the past couple of years.*** The sheer size of the global oil industry and the much larger volumes of oil (and hydrocarbons, in total) traded daily in both physical and financial terms enable effective price risk management. Smaller and less liquid metals markets tend to be more prone to influence and occasional manipulation. A collapse in nickel trading in March 2022 offered ample illustration (Figure 6). More important are the lack of transparency and indeterminant price signals, or lack of price signals altogether, that characterize metals markets today.
- **Old and New Insecurities**: Politics around natural resource endowments have always been fraught. Pressures for access, geopolitical competition, sustainability, markets and prices, and more are combining to add complexities that will test governance skills. An assumption has been that moving away from legacy fuels would ease insecurities (Figure 5). ***Instead, shifts to metals dependent energy technologies not only are heightening existing insecurities but creating new ones.***

Any single one of these challenges would be enough to contend with. All are playing out together in various ways, with various time horizons, and with many impenetrables.

None of this means there will not be success cases for mining, minerals, and materials and potential breakthroughs. Rather, it is an acknowledgement, based on available data and understanding of the myriad commodities, businesses, and fundamentals, that the path may be much longer and more arduous than typically presented to public audiences.

Much of the political debate around materials challenges is embedded in conventional wisdom that use of fossil fuels must end. "Ending fossil fuels" affects deliverability of materials from hydrocarbons value chains, along with much else, not least national and economic security and resilience. As an aside, I think it is safe to say that we at the Baker Institute are as concerned about integrity of investment flows to our domestic oil and gas industries as we are with possibilities for regaining domestic mining and minerals processing capacity.[2]

For the U.S. and Europe concerns about competitiveness revolve around manufacturing of finished goods like wind and solar equipment and battery electric vehicles (BEVs) along with high end electronics and microelectronics that slop into defense applications. ***A higher comfort level with China's role as dominant supplier at least for civilian apps could ease those ructions.*** That said, more creative conversations about China, and shifting global balances of power, are hard to come by.[3]

Much less attention is paid to the demand side of the energy and materials equation. That is starting to change, as barriers and costs associated with supply side dilemmas permeate discussions. Realizations are growing that new technologies that seem so appealing for efficiency gains are proving to be energy hogs. Humans need minerals for life. We utilize minerals and the metals and chemicals derived from them in every industrial sector and across a host of consumer products and services. ***Demand sensitivities absolutely will surface if a push to accelerate energy apps runs up against immovable supply curves.*** Cost increases become embedded in vehicles of all types, appliances, housing construction, medical equipment, and a great deal more.

Here I call out the Consumer Energy Alliance, where I serve on the board of directors. We are united in efforts to draw attention to the consumer side of the equation and the vital importance of consumer energy education and STEM education[4] without which not much of workforce readiness will be achievable. In testimony provided last January[5], they noted that "[in 2023], 52% of Americans reported that they did not have emergency savings to cover unexpected increases in expenses due to inflation and rising energy costs[6] … Restrictions on natural gas and inadequate pipeline infrastructure have caused many regions of the U.S. to see dramatically higher electricity bills … To underscore this point and the impact of energy policies that eliminate affordable and reliable energy choices, natural gas pipeline restrictions in the Northeast contributed to electricity bills that were forecast to rise by as much as 64%, or by nearly $1,500 a year for the average Massachusetts household."[7]

Costs also become embedded in defense industry products. ***Materials security for defense can benefit from improved domestic supply chains but defense industries cannot count on that within planning time frames and so may push for other measures.*** Defense, while a much-reduced slice of global materials consumption, remains a firm line in the sand. Advances in materials and technologies have long slopped back and forth between civilian and defense uses as ripples from innovations broaden. Military bases are under pressure to shift to “clean” energy sources and service branches to “clean” fuels and electric transport. Field units and personnel need mobile power. From drones to satellites, weapons systems are evolving rapidly. Pandemic supply chain ructions, new geopolitical tensions, and an upsurge in hard conflicts brought new strategic and tactical situational awareness to materials supply security for defense industries. China and that country’s influence looms large in worries about defense readiness for which materials and manufacturing supply chains are integral. ***Materials security for defense can benefit from improved domestic supply chains but defense industries cannot count on that within planning time frames and so may push for other measures.***

Many ideas exist for how to innovate in minerals and metals extraction.[8] Many projects target lower grade resources which require more intensive processing with distinct tradeoffs. In part this reflects realities in the resource base and access to resources for exploitation. Not all ideas are new — “in situ” mining has long been held out as a possibility for fuels (uranium and oil shale, for instance) and even essential metals. Capturing remaining products embedded in mined waste is a high and increasing priority but bears many technical and environmental considerations. Mining and processing are targets for digitization and automation (artificial intelligence, anyone?) as any other economic sector to speed exploration and enhance efficiency. ***Technology does not alter underlying geology, but it can stretch the boundaries for commercial recoverability.*** For the ultimate geology game changer, frontiers — the oceans, space? — attract plenty of imagination.

If we cannot, or will not, extract as much raw material as believed will be needed for our energy futures, where does optionality lie? Most often the focus is on “Re-X” — how to best utilize “reuse, repair, remanufacture, repurpose, refurbish, or recycle”[9] to reduce the need for raw materials and improve “sustainability from a systems perspective.”[10] In particular, recycling is held up as a key solution for minerals and metals and most views are that we cannot pursue metals-dependent energy futures without it. ***Recycling is an industrial activity that entails its own requirements and bears its own sustainability tradeoffs.***

Or we substitute, an age-old solution to persistent dilemmas. To the extent possible in performance and safety we substitute in response to acquisition cost — aluminum for copper being a common swap for electrical conductivity. ***Could we leapfrog challenges in metals with advanced materials?*** Carbon-based materials predominate across sectors, segments, and end use applications. We have swapped plastics for metals for decades to reduce weight and cost and improve performance (Figure 5). Carbon nanotube fiber, CNTF, could unlock new options for applications that require electrical and thermal conductivity _and_ tensile strength, for all of which CNTF excels. CNTF can displace metals for conductive wire and cable that can service vehicles, aircraft, and power grids. It offers new opportunities from wearables (including superior properties to Kevlar) to construction and fabrication materials (think state of the art aviation and space craft), to electronics (including flexible hybrid electronics for implants to support health monitoring), to targeted delivery of new cancer treatments. In a world in which "green" aluminum, copper, and steel suppliers will seek 30-40 percent price premiums, advanced materials like CNTF represent a breakthrough. The desired price point for carbon fiber long has been $5/kilogram (kg) and CNTF at scale is more cost effective (Figure 7).

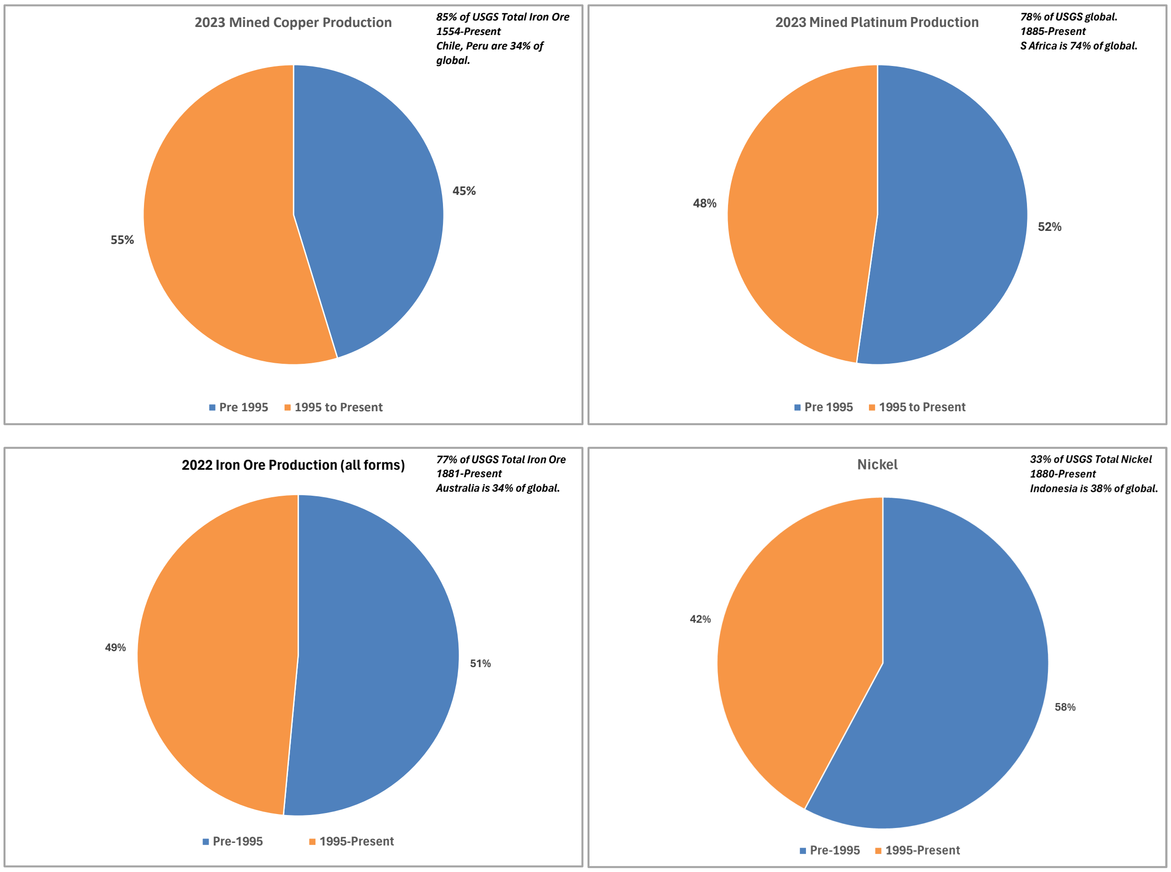
An important concept that I have put forth in previous testimony,[11] is that ***governments should place materials first for policy making before attempting to pick technology "winners."*** Such an approach might seem limiting, but would also avoid capital destruction, leaving both taxpayers and private investors better off. Putting materials first is not an idle thought given the vast amounts of capital committed to green energy already, with the prospect of much more to reach typical "net zero" GHG targets, all amplified by efforts to bolster other essential industries like materials dependent semiconductors. Along the meandering trail of energy and industrial policy making in the U.S., we have been to this place many times before. Over the past 50 years, developers have hit walls attempting to execute with materials limitations. Materials constraints — supply, cost, quality, performance — were relevant during the Carter era Synfuels Corporation push, as civilian nuclear was launched, through the many past waves of hydrogen enthusiasm, in early attempts to deploy carbon capture at scale, as inventors experimented with early battery chemistries and as they pushed forward to attain performance for vehicles equivalent to gasoline and diesel.

What does progress look like? The wind industry provides a snapshot. The eight-ton stainless steel turbine blades in an early 1980s wind energy design at Medicine Bow, Wyoming[12] gave way to fiberglass and today's sophisticated thermoplastics, reducing weight and enabling much larger rotor diameters. These innovations brought carbon-based materials firmly into the picture for wind energy as they have for so much else in the energy sphere, indeed in modern life. The need for better, more durable carbon fiber composites is widely recognized in order to extend the life of wind power and other equipment. CNTF is particularly well suited to progress beyond current carbon fiber in turbine blades and to displace metals for conductive wiring and cable and other fabricated parts. ***This means hydrocarbon value chains, the most amenable source of carbon for materials, are as critical to our energy futures, if not more so, as are mining and non-fuel minerals.***[13] The integrity, soundness, and preservation of both fuel and non-fuel minerals are necessary for success.

And therein lies one of many lessons in materials transitions. It may not be at all what people expect.

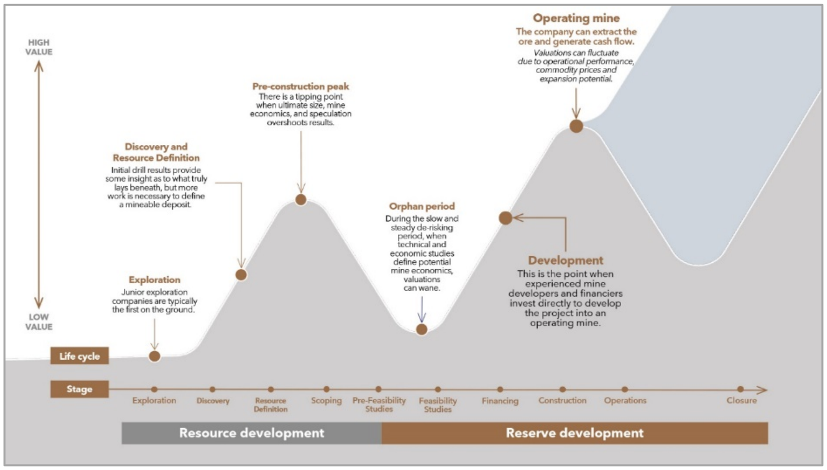
Figures and Tables

Figure 1: Lens on Asset Maturity — Copper, Platinum, Iron Ore, Nickel



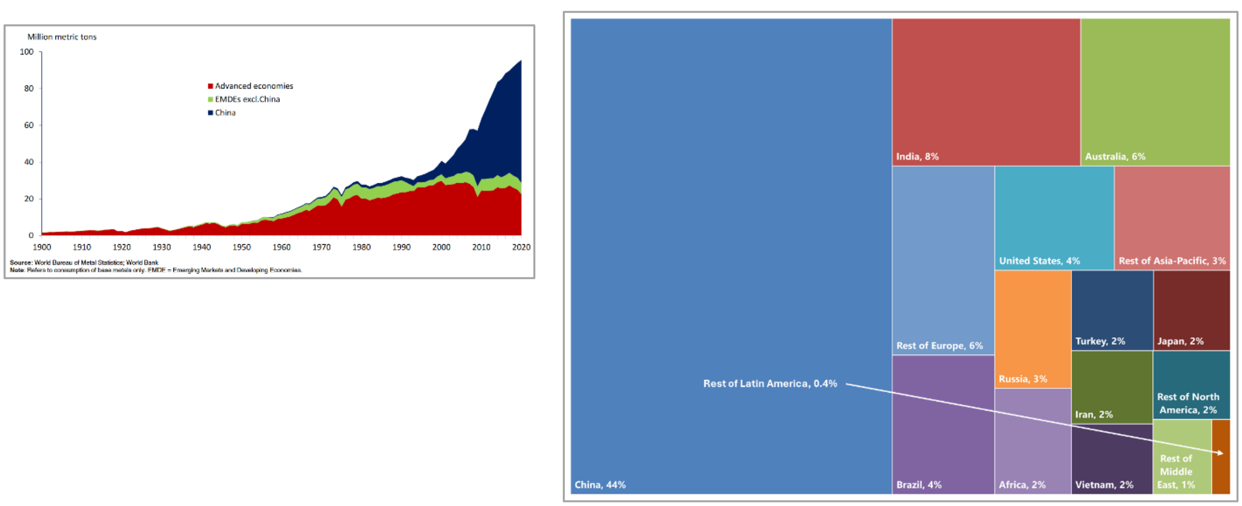
Source: Compiled by M. Michot Foss using SPG accessed via license. Iron ore is concentrates, fines, lump, pellets. Total cash cost is operating expenditure or opex.

Figure 2: A Version of the Lassonde Cycle



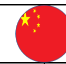
Source: Taken from Resource Capital Funds.[14]

Figure 3: Global Metals Demand and Market Shares (Based on Total Minerals Tonnage, 2022)



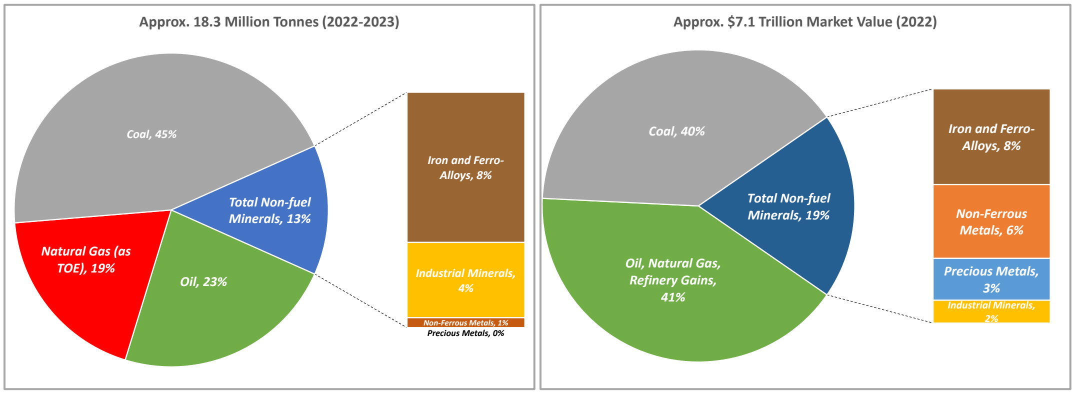
Source: World Bank[15] and M. Michot Foss using CES database. Total of 16 billion metric tonnes includes cement, aggregates, stone, all iron products reported by USGS as compiled by CES.

Table 1: U.S. Competitiveness, Selected Metals and Years

Facility						
		1970	1995	2022	1995	2022
Copper (tellurium, PGMs, arsenic, bismuth, antimony)						
Mines		1.6	1.9 / 19%	2.3 / 21%	0.4 / 4%	1.9 / 9%
Metal (Smelters)		1.6	1.3 / 6%	1.0 / 4%	0.7 / 6%	11.0 / 42%
1970 World Share		23%				
Zinc (indium, germanium, gallium)						
Mines		0.5	0.64 / 9%	0.77 / 6%	0.95 / 13%	4.2 / 32%
Metal (Smelters)		0.9	0.6 / 12%	0.22 / 2%	1.1 / 21%	6.7 / 50%
1970 World Share		18%				
Lead (bismuth, tin, antimony)						
Mines		0.5	0.4 / 14%	0.3 / 6%	0.4 / 13%	2.0 / 45%
Metal (Smelters)		1.2 (50% primary)	0.4 / 10%	0.0 / 0%	0.4 / 14%	~5.7 / 46%
1970 World Share		35%				
Alumina (gallium)/Aluminum Metal						
Mines		Alumina — 6.6	4.5 / 11%	1.2 / 1%	2.2 / 5%	76.0 / 54%
Metal (Smelters)		Metal — 3.6	3.4 / 17%	0.9 / 1%	1.9 / 10%	40.0 / 57%
1970 World Share		34% (metal)				

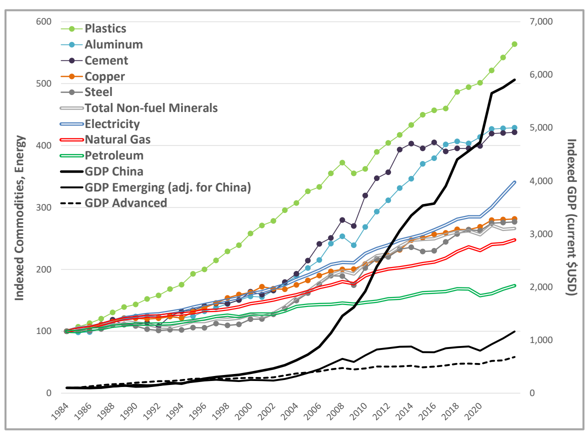
Sources: Based on work by Michael S. Moats, Missouri S&T. CES database and other sources for 2022 update. Data are million tonnes and % share of world. Co-product potential in parentheses.

Figure 4: Global Fuel and Non-fuel Commodities Market Shares by Tonnage (left) and Value (right)



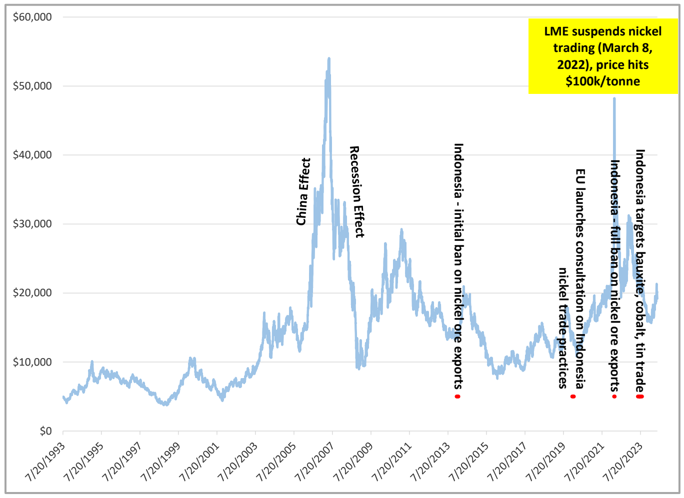
Source: M. Michot Foss estimations using EI, WMD, USGS. Natural gas as tonnes of oil equivalent, TOE (left).

Figure 5: Growth in Key Commodities (Indexed to 1984)



Source: M. Michot Foss using Energy Institute (EI), U.S. Geological Survey (USGS), World Mining Data (WMD), American Chemistry Council (ACC), International Aluminum Institute (IAI), International Copper Study Group (ICSG), Steel Institute, International Monetary Fund (IMF).

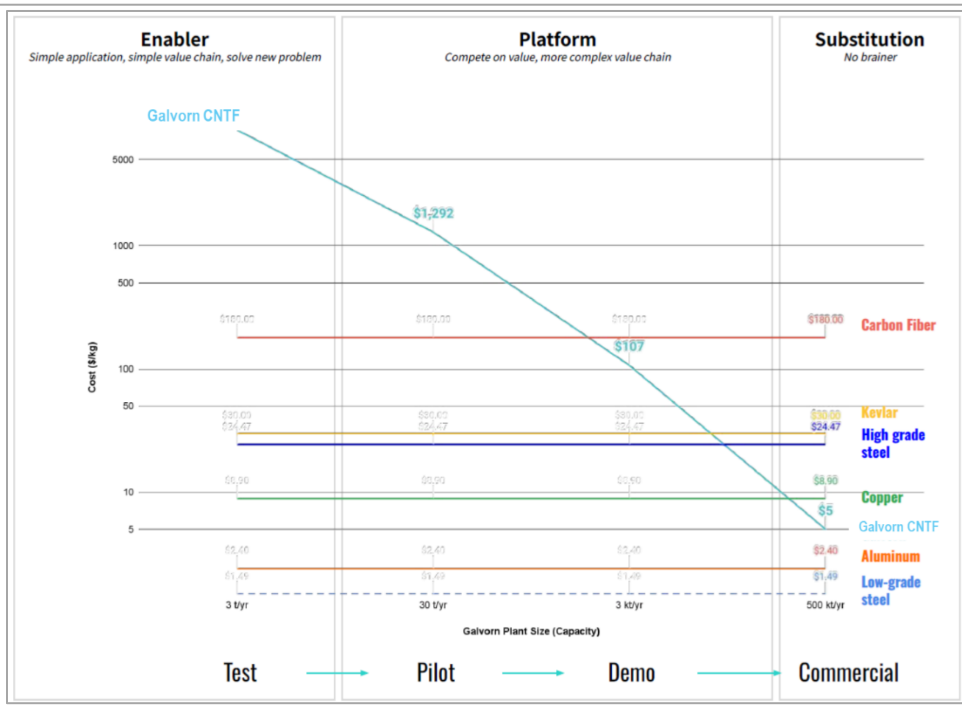
Figure 6: Nickel Trading Events



Source: M. Michot Foss using SPG, accessed via license, and other sources including U.S. International Trade Commission.

Figure 7: CNTF Product Comparative Properties (top) and Cost Reductions (bottom)

	Properties								Emissions		Energy	Price	
	Strength (GPa)	Modulus (GPa)	Density (g/cc)	Flex Life (cycles)	Electrical Conductivity (MS/m)	Thermal Conductivity (W/m-K)	Corrosion Resistance	Bio-compatibility	GHG Intensity (kg CO2/kg)	Total GHGs (MT CO2)	Energy (MJ/kg)	($/kg)	Performance Levelized ($/kg)
Steel**	1	200	8	100,000	3.4	50	Average	Non-toxic	1.8	2900	80	$24.47	$244.70
Aluminum	0.1	72	2.7	10,000	37	205	Poor	Not Implantable	12	750	210	$2.40	$72.00
Copper	0.2	100	9	10,000	58	385	Poor	Not Implantable	3.7	100	60	$8.90	-
Carbon Fiber**	6.4	200-400	2.1	10,000	0.1	200 - 1000	Excellent	Non-toxic	25	3	410	$180.00	-
Aramids (Kevlar)	3	130	1.4	1,000,000	Insulating	0.04	Excellent	Non-toxic	87	9	?	$30.00	-
GALVORN CNTF	3	200	1.6	1,000,000	10	446	Excellent	Non-toxic	-50 (at scale)	-2700 (at scale)	44 (at scale)	≈$5 (at scale)	



Source: Provided by DexMat, https://dexmat.com/.

Notes

[1] See https://www.bakerinstitute.org/center/center-energy-studies#-4062963801.

[2] Michelle Michot Foss, February 8, 2021, The "Criticality" of Minerals for Energy Transitions. Hydrocarbons? Yes, Hydrocarbons, Center for Energy Studies, Energy, Minerals & Materials, Commentary, https://www.bakerinstitute.org/research/the-criticality-of-minerals-for-energy-transitions-hydrocarbons-yes-hydrocarbons. Also see testimonies by Kenneth B. Medlock III and Michelle Michot Foss before the Senate

Committee on Natural Resources, Hearing to Examine the Use of Energy as a Tool and a Weapon, March 10, 2022, https://www.bakerinstitute.org/research/senate-testimony-use-energy-tool-and-weapon.

[3] See Gabriel Collins, November 13, 2023, The US-China Economic Relationship Needs 'Robust De-Risking,' and a Little Strategic 'Decoupling', Center for Energy Studies, Policy Brief, Baker Institute for Public Policy, https://www.bakerinstitute.org/research/us-china-economic-relationship-needs-robust-de-risking-and-little-strategic-decoupling.

[4] See https://research.rice.edu/rstem/ and https://ceef.org/.

[5] See testimony provided by David Holt, President, Consumer Energy Alliance, House Committee on Natural Resources, Subcommittee on Energy and Mineral Resources, hearing on Examining the Biden Administration's Limits on Access to the OCS: Impacts on Consumers, States, and Operators, January 11, 2024, https://naturalresources.house.gov/calendar/eventsingle.aspx?EventID=415354.

[6] See https://www.bankrate.com/banking/savings/emergency-savings-report/#:~:text=More%20than%20one%20in%20five%20Americans%20have%20no%20emergency%20savings&text=Nearly%20one%20in%20three%20(30,percent%20of%20people%20in%202022.&text=Nearly%20one%20in%20four%20(22,they%20have%20no%20emergency%20savings..

[7] See https://www.wcvb.com/article/electric-bills-could-increase-64-percent-this-winter-in-massachusetts-2022-2033/41312993.

[8] Michelle Michot Foss, December 20, 2022, Defining the 'Minerals Heartland' of the Future — From Africa to Central Asia, Center for Energy Studies, Energy, Minerals & Materials, Research Paper, Baker Institute for Public Policy jointly with Future Minerals Forum, https://www.bakerinstitute.org/research/defining-minerals-heartland-future-africa-central-asia and February 8, 2024, Mining, Minerals, and Materials in the Age of Sustainability and Alliances, Future Minerals Forum and Center for Energy Studies, Energy, Minerals & Materials, Research Paper, Baker Institute for Public Policy jointly with Future Mineral Forum, https://www.bakerinstitute.org/research/mining-minerals-and-materials-age-sustainability-and-alliances .

[9] Rachel A. Meidl, August 9, 2023, Schrödinger's Cat Paradox: Carbon Is the Enemy. Carbon Is Not the Enemy, Center for Energy Studies, Issue Brief, https://www.bakerinstitute.org/research/schrodingers-cat-paradox-carbon-enemy-carbon-not-enemy. Meidl, July 29, 2021, Disentangling Circular Economy, Sustainability and Waste Management Principles, Center for Energy Studies, Issue Brief, https://www.bakerinstitute.org/research/disentangling-circular-economy-sustainability-and-waste-management-principles. Meidl, August 3, 2021, A Circular Economy Doesn't Necessarily Imply Sustainability, Center for Energy Studies, Commentary, https://www.bakerinstitute.org/research/circular-economy-does-not-necessarily-translate-sustainability.

[10] Rachel A. Meidl and Kenneth B. Medlock III, November 8, 2023, The Pride and Prejudice of Sustainability: Rethinking Sustainability From a Systems Perspective, Center for Energy Studies, Policy Brief, https://www.bakerinstitute.org/research/pride-and-prejudice-sustainability-rethinking-sustainability-systems-perspective.

[11] Michelle Michot Foss, May 5, 2021, Minerals & Materials Supply Chains — Considerations for Decarbonizing Transportation, testimony before the U.S. House of

Representatives, Committee on Energy & Commerce, Subcommittee on Energy, Hearing on "The CLEAN Future Act: Driving Decarbonization of the Transportation Sector", https://www.bakerinstitute.org/research/minerals-materials-supply-chains-considerations-for-decarbonizing-transportation.

[12] James Bailey, 2014, The Medicine Bow Wind Energy Project, Historic Reclamation Projects, U.S. Bureau of Reclamation, https://www.usbr.gov/history/ProjectHistories/Wind%20Electric%20Power%20Project.pdf. The author visited (and entered the nacelle of) the Medicine Bow all-metal wind turbine in 1984.

[13] See endnote 2.

[14] See https://resourcecapitalfunds.com/insights/mining-and-minerals-101/phases-mining/. Other versions with useful background are https://www.smallcapinvestor.ca/post/the-lassonde-curve-understanding-the-mining-life-cycle, https://www.usfunds.com/resource/the-journey-from-exploration-to-production-understanding-the-lifecycle-of-a-mine/ (which injects some humor into the storyline), and https://www.visualcapitalist.com/visualizing-the-life-cycle-of-a-mineral-discovery/ (which informs other web sites).

[15] From World Banks 2022 commodity markets report, https://www.worldbank.org/en/research/publication/commodity-markets.