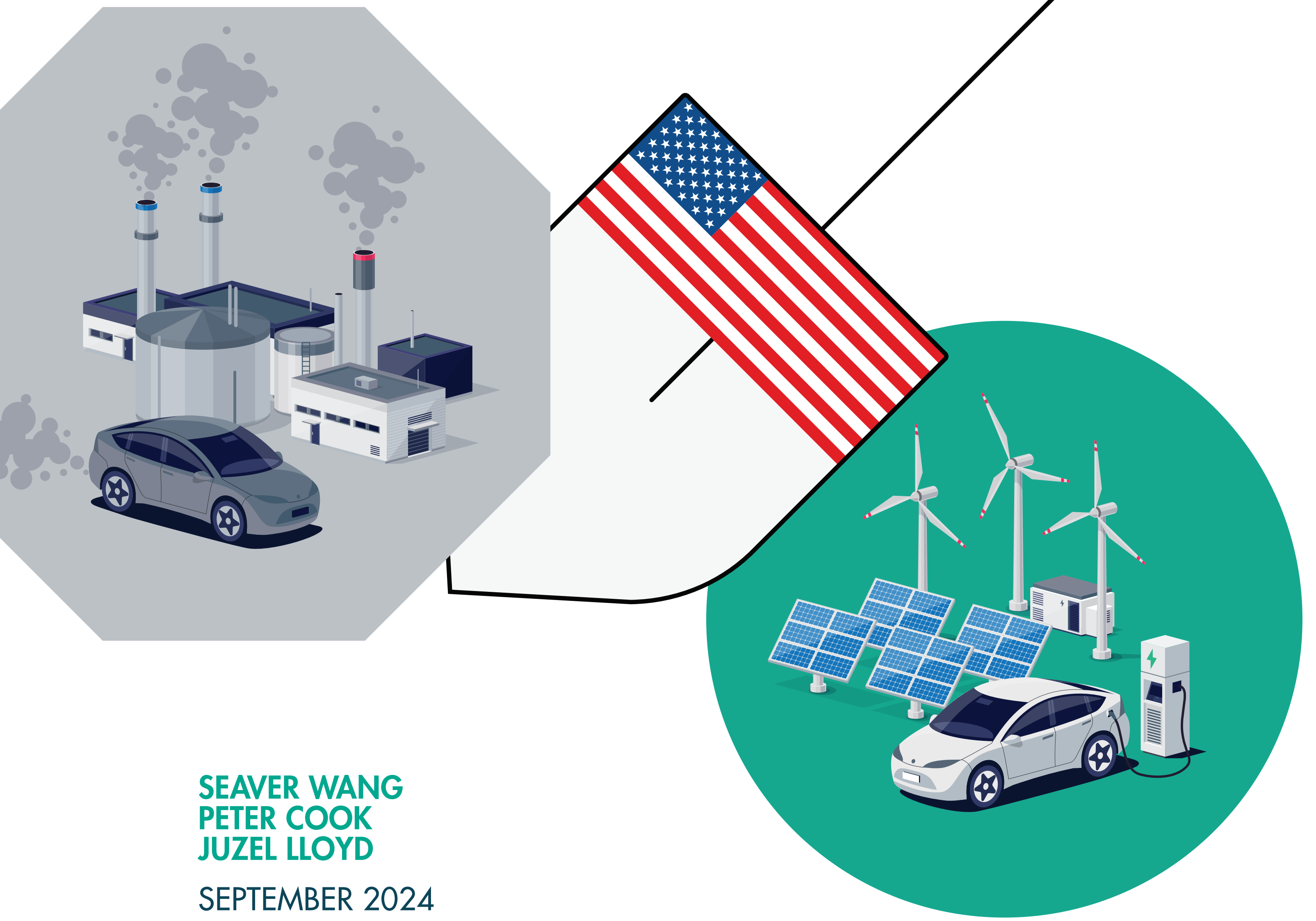
BREAKTHROUGH INSTITUTE

METALS FOR THE FUTURE: WHAT MINERALS WILL THE U.S. NEED FOR CLEAN TECHNOLOGIES?

PRIORITIES FOR BUILDING ENERGY TRANSITION CRITICAL MINERAL SUPPLY CHAINS



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EXECUTIVE SUMMARY

Currently, the United States seeks to strike a difficult balance between competing for the leading edge of advanced energy technologies like batteries and solar photovoltaics and protecting those industries from vulnerable overdependence on imports of key raw materials and components. Left unaddressed, mineral supply chain constraints may ultimately force policymakers to choose between pursuit of climate ambitions with mass-imported goods or cultivating domestic capacity in strategic industries. Avoiding this dilemma requires strong public policy support, as prevailing market incentives exhibit a regular bias toward cheaper and often highly problematic critical mineral imports from overseas.

Yet we cannot design good policy without a more concrete understanding of future national mineral demands. Accelerating trends such as increased adoption of new energy and vehicle technologies offer the U.S. the potential to bolster national energy abundance and seize leadership in emerging global industries with strong growth potential. But critical mineral inputs for these industries remain a persistent weak point in U.S. industrial capabilities and strategy.

This report estimates U.S. mineral needs for power and road transportation sector decarbonization by 2050, provides policy guidance on the states of those mineral supply chains from a U.S. perspective, and identifies which commodities warrant prioritization in national critical minerals strategy. This empirical quantification better connects policy efforts focused on critical minerals with the possible magnitude of future national mineral demands.

Electricity generation, electricity transmission, and electric vehicles will drive demand for raw materials like aluminum, nickel, and copper that matches or exceeds economy-wide national consumption today. We identify graphite, lithium, and rare earth elements, in particular, as priority energy technology minerals for which current production by the U.S. and its allies and partners falls well short of likely future needs (Figure ES 1).

Electric vehicles carry especially significant weight in determining future U.S. mineral needs. Even if we assume that nickel-free and cobalt-free lithium-iron-phosphate (LFP) battery packs comprise 60% of the future market share for road vehicles of all classes, establishing reliable supplies of battery-grade nickel and cobalt may remain a major challenge. Highly ambitious electric vehicle adoption goals or large-scale efforts to export American-made EVs overseas could consume double the rare earth elements, nickel, and copper over the next 25 years relative to nationwide construction of clean power and transmission infrastructure.

Without muscular industrial policy and economic diplomacy, critical mineral demands will force policymakers to prioritize between large-scale deployment of advanced energy technologies and resilient, domestically-bolstered supply chains. Underinvestment in secure supply chains may leave the U.S. a mere mass importer of materials and equipment, ceding leadership in strategic technologies and accepting geopolitical vulnerabilities. Alternatively, immature supply chains risk saddling households, firms, and infrastructure projects with high costs and leaving better economies of scale beyond reach.

In general, these results emphasize the importance of expanded domestic production alongside close international coordination for ensuring that the U.S. can meet future clean technology sector needs.

Key findings:

- Electric vehicles account for two-thirds of future national demand for many clean energy minerals, with graphite, lithium, and rare earth elements emerging as key priorities.

  Graphite: Demand for battery graphite will grow to 1 million to 1.5 million tons per year—roughly 16 and 25 times greater than the amount contained in domestically sold EVs in 2023, with a negligible quantity produced domestically.

  Lithium: At roughly 3,000 tons per year, current U.S. production can only meet 2-3% of future lithium demand from battery deployment (100,000 to 150,000 tons per year).

  Rare earth elements (REE): Electric vehicle motors and wind turbines alone may drive REE demand that exceeds U.S. production by over 50% over the next decade.

  Nickel and cobalt: Even a large market shift from nickel-manganese-cobalt batteries to nickel-free and cobalt-free lithium-iron-phosphate batteries will not eliminate heavy U.S. reliance on nickel and cobalt imports from China, particularly given minimal U.S. cobalt production.

- Broadly, clean energy technology usage will drive sizable demand for aluminum, nickel, copper, and steel.

  Aluminum: Annual deployment of electric vehicles, renewables, and transmission could use as much aluminum as the entire U.S. economy does today.

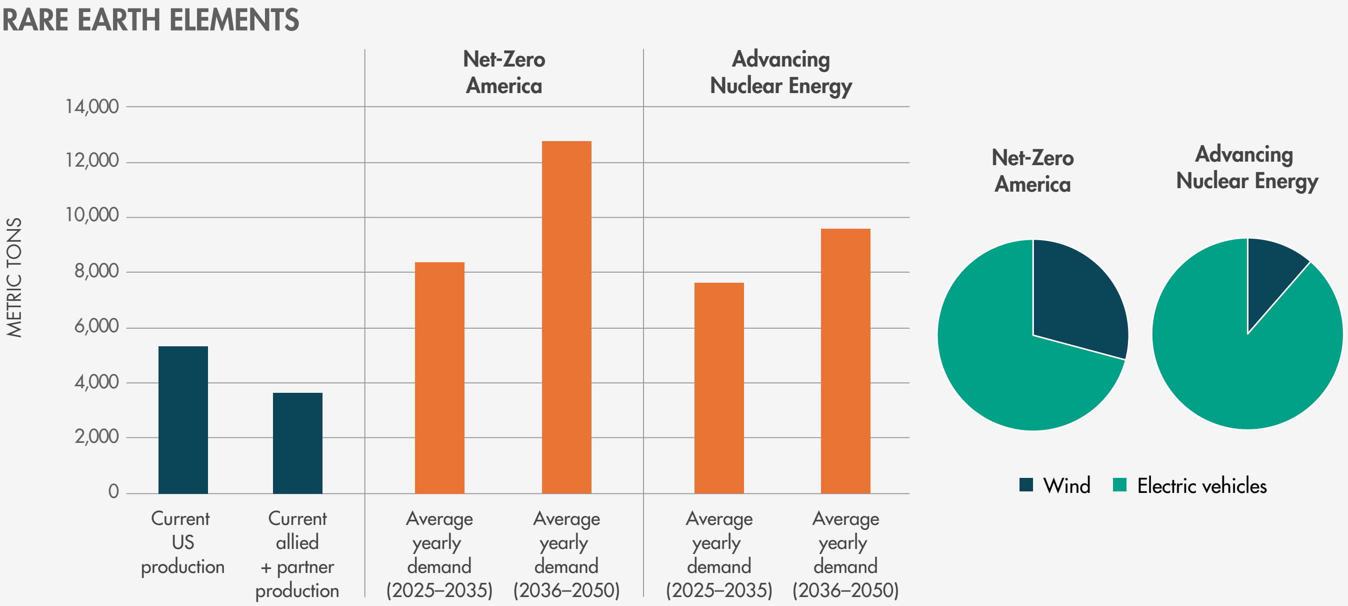
  Nickel: Clean technology usage of nickel may grow to 200-300% of current national consumption.

  Copper: Clean technology copper consumption may reach 1.1 to 1.6 million tons per year, compared to U.S. production of around 1.25 million tons in 2023.

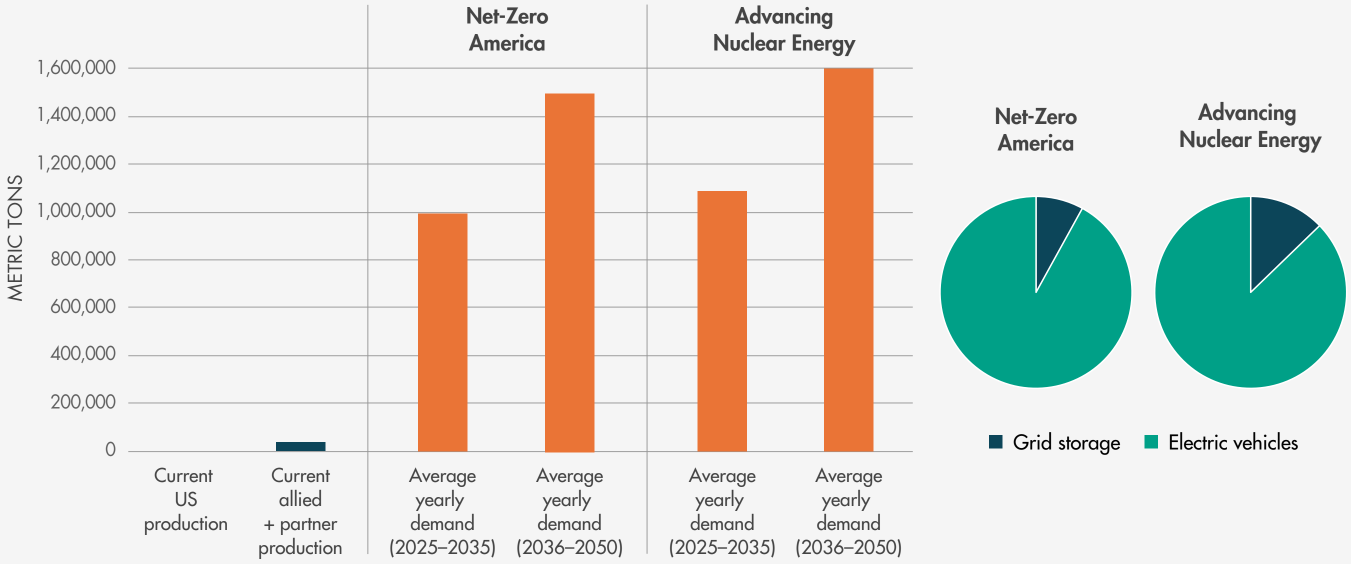
  Steel: Future clean technology usage of steel may grow to match 23-38% of current national consumption.

- The United States must rely on diversified trade alongside expanded domestic production to meet future demand for many clean energy minerals.
- Financial support for processing should prioritize minerals with limited existing domestic capacity and smaller market volumes, in order to reduce risks for trailblazing projects and avoid costlier policy support for commodities with larger trade flows.
- Expanding domestic mining and processing of critical minerals will ultimately require progress across multiple policy areas including permitting, trade, targeted financial support, and coordinated use of financial and physical tools and contracts.

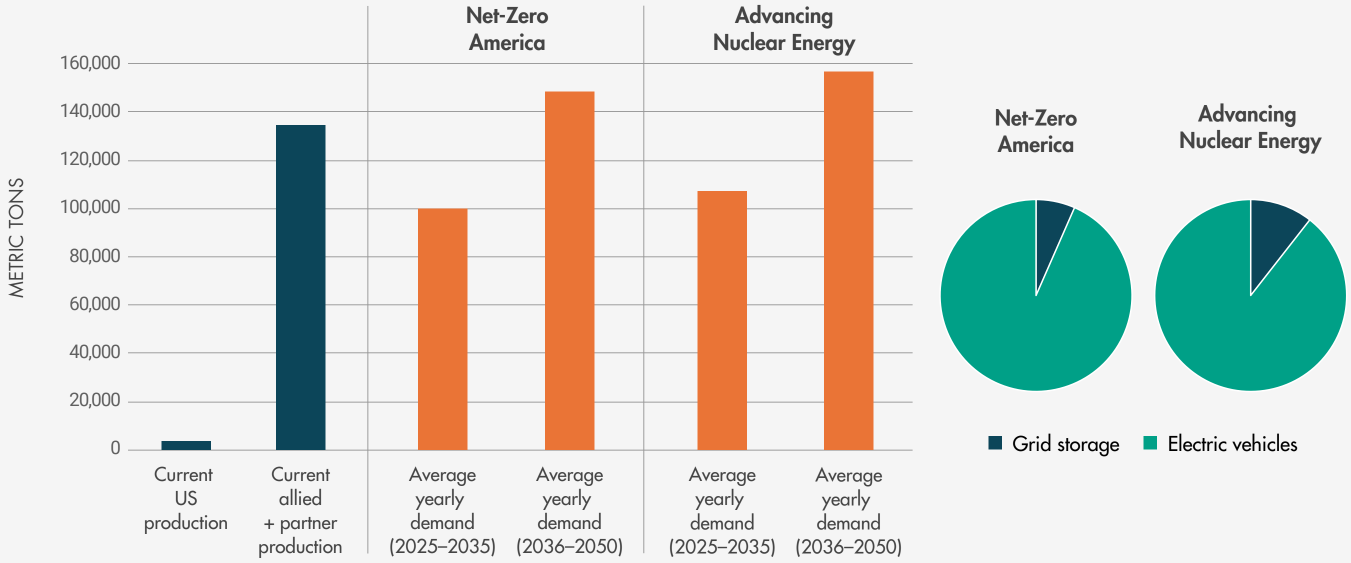
Figure ES 1: Current annual mine production of rare earth elements, graphite, lithium, nickel, and copper by the U.S. and its free trade partners and allies, relative to estimated future U.S. yearly demand from clean electricity infrastructure and electric road vehicles (bar graphs). All masses are expressed in tons of contained elemental metal. Share of clean power and electric road transport sector cumulative mineral consumption by sub-sector is shown for both examined scenarios (pie charts). Scenarios are the Princeton Net-Zero America study's E+ scenario and the Breakthrough Institute's Advancing Nuclear Energy study's Low Cost, Low Learning scenario. US production is a 5 year average of mining and recycling. Overseas country production considers mining only. Rare earth elements include only neodymium, dysprosium, praseodymium, and terbium based on proportions from USGS Mineral Yearbooks and company reports. All production data from USGS 2024 Mineral Commodity Summaries except US lithium mine production from individual company reports.


RARE EARTH ELEMENTS

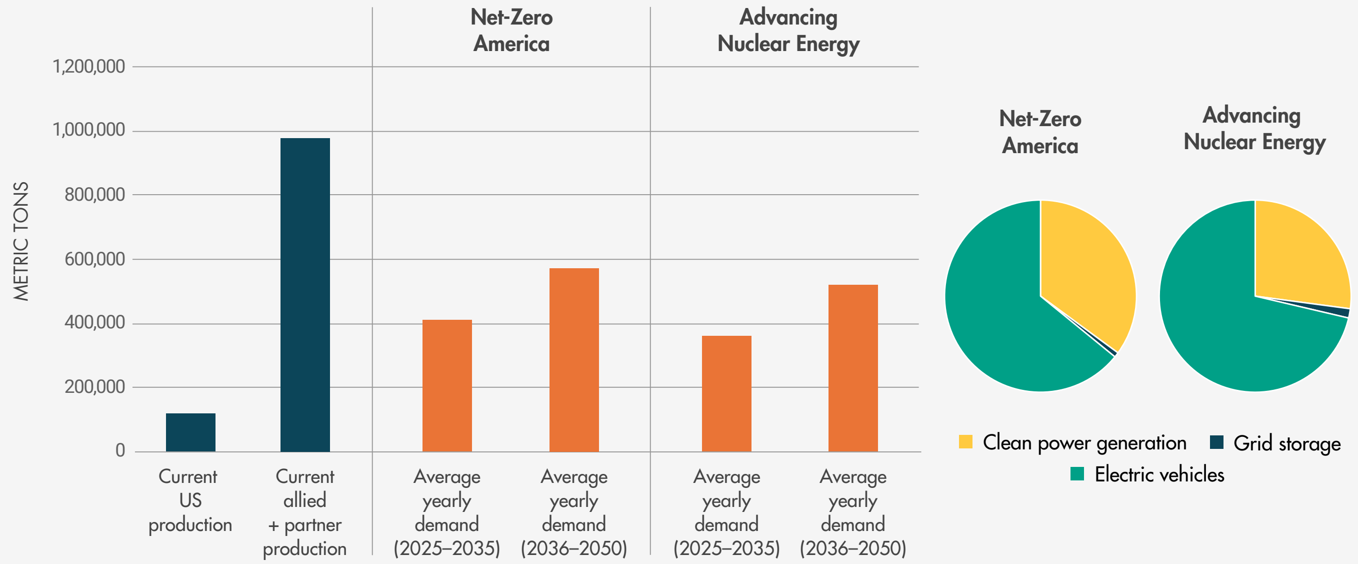
GRAPHITE



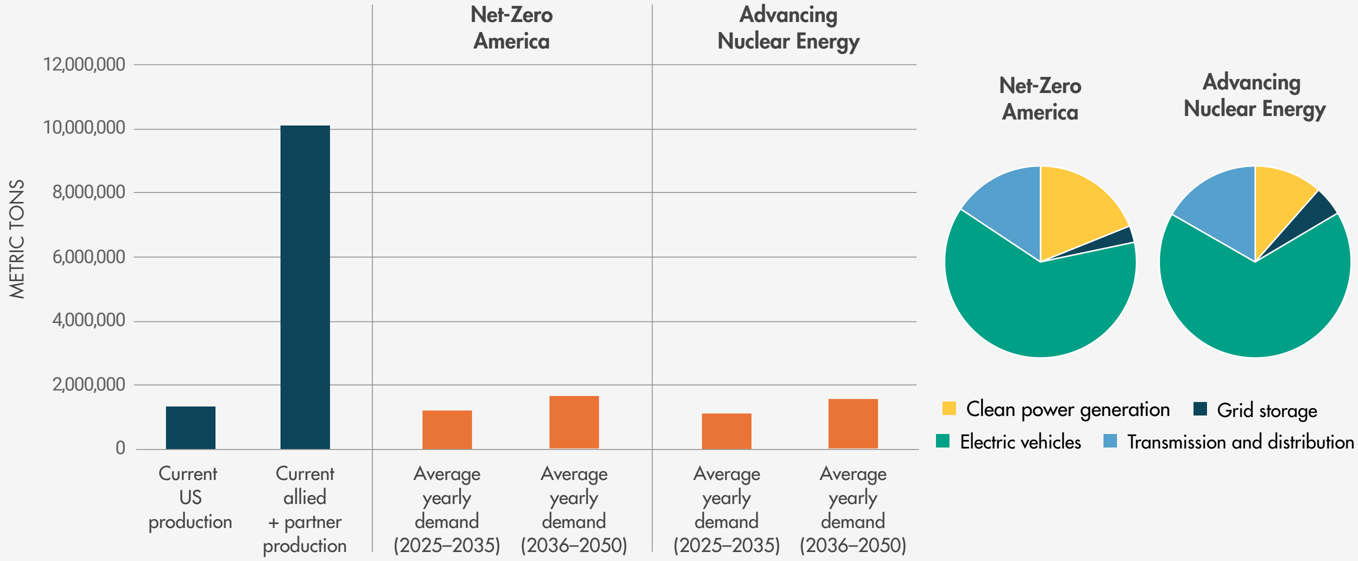
LITHIUM



NICKEL



COPPER



Approach to calculations

In this report, we present modeling results from investigating potential nationwide deployment of solar, wind, nuclear, and utility-scale batteries by 2035 and 2050 under two different pathways (Table 1):

- **A high-renewables pathway**—the Princeton Net-Zero America study's E+ scenario.[1]
- **A balanced renewables and nuclear pathway**—the Breakthrough Institute's Advancing Nuclear Energy study's Low Cost, Low Learning scenario.[2]

We multiplied these modeled deployment projections with quantitative mineral requirements for clean electricity generation technologies and battery technologies (Table 2), using values presented in recently published Breakthrough Institute reports and co-authored papers. To these results, we added mineral requirements for future transmission network expansion and electric road vehicle adoption based on the Princeton Net-Zero America study's E+ scenario. We note that our analysis considers the electricity and road transportation sectors only, and does not cover mineral requirements for sectors like hydrogen (electrolyzers, fuel cells), residential appliances (heat pumps, electric vehicle chargers), or rail/water/air/off-road transportation.

For the detailed methodology, refer to the Appendix.

Table 1: Projected scale of clean energy infrastructure and electric road vehicles in operation by 2050 in our two examined scenarios.

QUANTITIES OF TECHNOLOGIES OPERATING BY 2050	
Princeton Net-Zero America E+ scenario	**Breakthrough Institute Advancing Nuclear Energy Low Cost, Low Learning scenario**
Utility solar: 1319 GW Distributed solar: 186 GW Onshore wind: 1194 GW Offshore wind: 224 GW Advanced nuclear: 0 GW Li-ion battery storage: 1186 GWh Conventional nuclear (existing plants): 61 GW	Utility solar: 817 GW Distributed solar: 154 GW Onshore wind: 590 GW Offshore wind: 40 GW Advanced nuclear: 366 GW Li-ion battery storage: 1982 GWh Conventional nuclear (existing plants): 20 GW
313.6 million light-duty electric vehicles 9.3 million medium-duty electric vehicles 4.0 million heavy-duty electric vehicles 1,914,180 km of high-voltage transmission lines (1,033,200 km assumed operating today) 1,789,760 km of medium-voltage transmission lines (966,040 km assumed operating today) 25,650,020 km of low-voltage transmission lines (13,844,870 km assumed operating today)	

Table 2: Materials and minerals covered by this analysis. Rare earth elements here include neodymium, dysprosium, praseodymium, and terbium.

iron in steel
non-steel iron
rare earth elements
aluminum
boron
cadmium
chromium
cobalt
copper
glass and fiberglass
graphite
lithium
lead
magnesium
manganese
molybdenum
nickel
niobium
phosphate
solar-grade polysilicon
silver
solar PV cover glass
tellurium
tin
titanium
tungsten
zinc

Note: *In this analysis, we did not constrain ourselves to the exact list of critical raw materials articulated by the U.S. Geological Survey. Although minerals see some overlapping use across sectors, we focused principally on the subset of key raw materials relevant for clean electricity technologies and electric vehicles, as opposed to critical minerals relevant for defense, semiconductor chips, or other sectors. While uranium plays a crucial role in clean nuclear power generation, the Breakthrough Institute will cover U.S. uranium fuel needs in the nuclear energy sector (low-enriched uranium fuel and high-assay low-enriched uranium, HALEU, fuel) in a separate upcoming published analysis.*

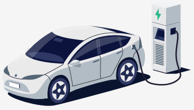
Key results

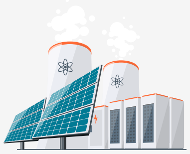
Electric vehicles

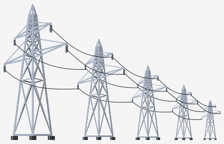
As a general rule, electric vehicles (EVs) will account for a dominant share of future demand for many clean energy minerals. High U.S. EV deployment will heavily drive clean tech sector consumption of battery metals, graphite, aluminum, and steel in particular. In the study period of 2025-2050, batteries for EVs may consume around 9 times the quantity of graphite and lithium that grid battery storage facilities do (Figure 1). Similarly, rare earth permanent magnets for EV motors may utilize 2.5 to 9 times the rare earth elements (REEs) used in domestically installed wind turbines. Light-duty EVs will make up the majority of electric vehicle mineral demands, accounting for 86% of materials utilized for EVs over the 2025-2050 period, with the remainder split evenly between medium-duty and heavy-duty EVs (Figure 2).

We assessed a relatively high EV adoption scenario, with EVs representing 62% of new light automobile sales by 2030 and reaching a figure of 313.5 million EVs in service by 2050. These results emphasize that insofar as policymakers seek to drive highly ambitious domestic adoption of EVs—and insofar as U.S. automakers and auto workers have ambitions to export U.S.-made EVs overseas at large scales—these vehicles will exert disproportionate influence over national critical minerals strategy. With the Inflation Reduction Act linking Section 30D EV tax credit incentives to requirements that battery manufacturers source an increasing percentage of battery minerals from the U.S. and its free trade partners, such dynamics particularly highlight continued supply chain gaps for graphite, REE, and lithium mining and processing.

Figure 1: Cumulative 2025-2050 consumption of battery graphite and lithium, rare earth elements, iron, aluminum, and copper as percentages of demand from each clean technology sector, based on estimated future U.S. technology deployment trends.

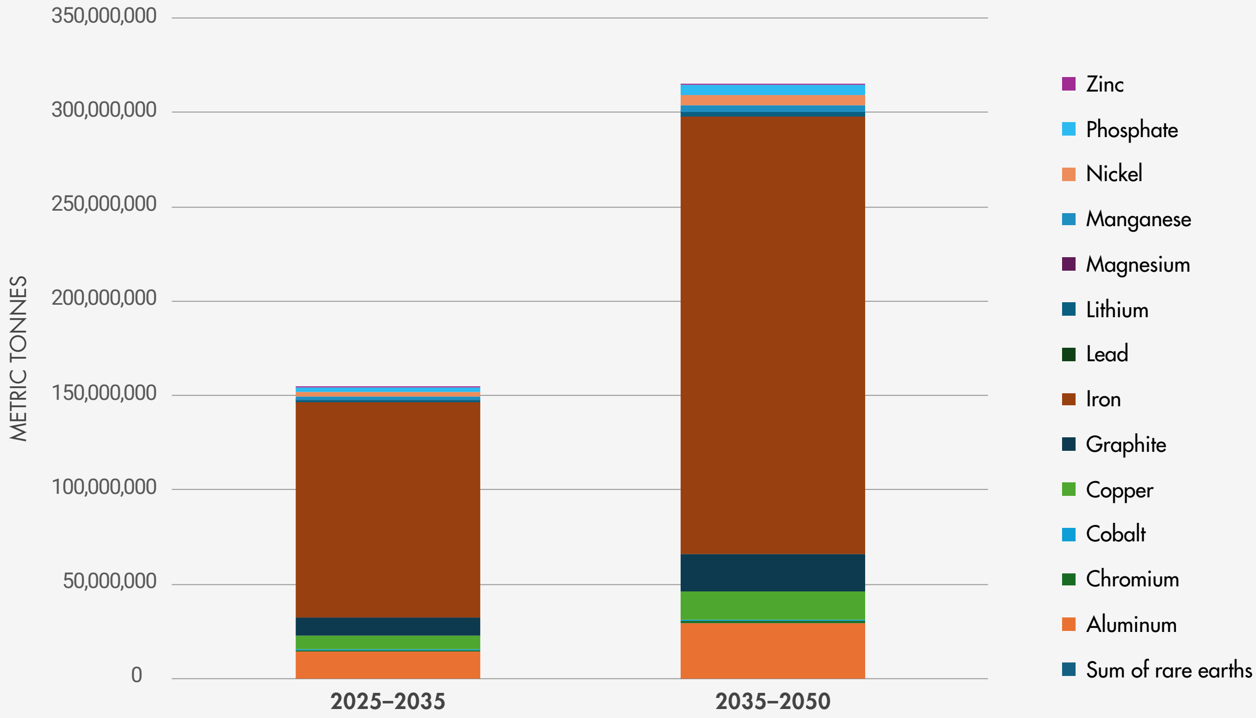






	ELECTRIC VEHICLES	CLEAN POWER GENERATION AND STORAGE	TRANSMISSION AND DISTRIBUTION
Battery graphite and lithium	87% to 92%	8% to 13%	None
Rare earth elements	71% to 89%	11% to 29%	None
Iron (in steel products)	51%	39%	10%
Aluminum	41%	22%	37%
Copper	63% to 67%	22% to 16%	15% to 17%

Figure 2: Cumulative future electric road transportation mineral requirements in the 2025-2035 and 2036-2050 periods.



Electricity sector decarbonization

In our study, the electricity sector (power generation, storage, and transmission) will utilize similar volumes of aluminum (59%) and iron (49%) demand as the electric vehicle sector over the next 25 years. While EVs may drive the lion's share of demand for many other minerals, electricity sector mineral requirements are nevertheless significant.

For example, while energy transition conversations frequently characterize nickel as a "battery metal," nickel consumption in stainless steel and other alloys used in wind turbines, solar farms, and nuclear power plants will account for a substantial fraction of future nickel demand. Wind, solar, and nuclear installations will consume 1 ton of nickel for every 1.9 to 2.7 tons of nickel used in EV and storage batteries for the 2025-2050 scenarios. Certain commodities exclusive to particular technologies, such as refined polysilicon and silver used in crystalline silicon solar modules and cadmium and tellurium used in thin-film solar modules, have minimal connection to EV supply chains and depend entirely on future power sector trends.

We also found that substitution of wind and solar with other, more minerals-efficient clean electricity generation technologies like nuclear or geothermal power may alleviate some mineral requirements. When we compared the relatively high-renewables Net-Zero America E+ scenario (~87% of total U.S. generation from wind and solar by 2050) with the relatively high-nuclear Advancing Nuclear Energy scenario (~44% of U.S. generation from wind and solar and 40% from nuclear by 2050), we found the latter scenario's power generation and storage sector will use 28% less nickel, 29% less copper, 33% less aluminum, and 50% less iron in steel products for the period 2025-2050. This is not a level comparison, as the Advancing Nuclear Energy scenario envisions 23.5% lower total electricity generation (7511 TWh in 2050) than the high-renewables Net-Zero America E+ scenario (9825 TWh in 2050).

Transmission and distribution infrastructure will also drive significant demand for a subset of minerals: aluminum, copper, and iron in steel products. Specifically, transmission network expansion will stimulate considerable aluminum demand due to aluminum use in conductor cables, on the order of 1.4 to 1.7 million tons per year over the 2025-2050 study period. The magnitude of future transmission network copper use over the same period—5.6 million tons of copper primarily in transformers and substations—may rival copper consumption for clean power generation and storage (5.6 to 7.8 million tons). Overall, nationwide clean power generation, storage, and transmission will utilize about one ton of copper for every two tons of copper installed in U.S. EVs over the next 25 years.

How might technology choices potentially affect future mineral demand?

The technological future is hard to predict, and given mineral supply chain adequacy challenges many stakeholders might simply hope that further innovation and efficiency improvements will eliminate any risk of future mineral constraints. While we should not dismiss the possibility of unforeseen breakthroughs, neither should a pragmatic approach to supply chain risks depend too heavily upon technical advances that may or may not materialize to the desired extent.

One trend that has led many analysts to express greater optimism about future nickel and cobalt supply needs, for example, is the exciting growth in the market share of nickel and cobalt-free lithium-iron-phosphate (LFP) electric vehicle batteries. LFP batteries offer lower cost but store less energy for the same battery pack weight compared to currently dominant nickel-manganese-cobalt (NMC) lithium-ion battery chemistries, imposing some range and performance trade-offs on electric vehicles.

This market shift toward LFP batteries is very real, such that our analysis assumed that all future power grid battery storage facilities will use LFP batteries given their lower cost and improved longevity (and the irrelevance of battery weight for fixed stationary applications). At the same time, our study generously assumed that 60% of all future U.S. light, medium, and heavy electric vehicles will adopt LFP battery packs, yet still projected future battery nickel and cobalt usage in the remainder of the EV sector that substantially exceeds current domestic production. In other words, a large-scale shift to LFP batteries still may not change the math that U.S. electric vehicles could utilize much more nickel and cobalt than the U.S. and its allies and free trade partners currently produce.

Even higher LFP battery pack adoption beyond 60% could alleviate such nickel and cobalt requirements, but it is also possible that slower-than-hoped LFP battery uptake could further increase nickel and cobalt demand. Our assumed 60% market share is aggressive relative to LFP batteries' current share of <10% of U.S. light-duty EV sales,[3] and may be infeasible for heavier vehicles considering the energy density advantages of nickel-manganese-cobalt (NMC) batteries for medium- and heavy-duty EVs.

All that considered, it is worth noting that next-generation battery chemistries like solid-state lithium-ion batteries, silicon-graphite or pure silicon battery anodes, or sodium-ion batteries do in theory have the potential to significantly alter future battery mineral consumption trends if and when they enter the market at scale.

Another hoped-for development related to clean technology mineral needs involves the replacement of REEs in electric vehicle motors and wind turbine magnetic drives. Nascent alternative magnetic drive technologies that do not rely on rare earth permanent magnets could potentially avert significant REE demand in the EV and wind sectors, but would need to achieve comparable performance, cost, and longevity. While many private and public research and development efforts—including grants from the Department of Energy's ARPA-E program—have long sought to develop and commercialize REE-free permanent magnets, these alternatives may not become market-ready for some time.[4]

Economic incentives will also continue to push wind, solar, and battery manufacturers to develop products that use less steel, aluminum, solar polysilicon, silver, or lithium while achieving similar or improved performance. However, such developments will typically only produce incremental improvements in material consumption. Additionally, innovations over the past decade have already exploited much of the potential for mineral use efficiency gains. For example, further reducing silicon losses from improved diamond wire slicing of solar polysilicon wafers may be difficult without increasing the rate at which thinner wafers break during the process. Additional improvements to wafer thickness and per-unit silicon usage are possible, but may require completely different manufacturing approaches.[5]

Finally, we note that if cadmium telluride (CdTe) thin-film solar photovoltaic modules retain a sizable market share (10-25%) of the future U.S. utility-scale solar market, implied annual tellurium usage in domestic deployed capacity could exceed 27%-102% of global tellurium production. Future trends in the share of CdTe thin-film and alternative thin-film solar cell types that use critical minerals like indium, germanium, or selenium thus pose some possible implications for national consumption of more exotic minerals, should thin-film solar technologies experience a resurgence.

How does clean technology usage of minerals compare to overall economy-wide supply and demand?

Future national demand for many minerals depends on long-term economic conditions and technological developments across the whole range of economic sectors, making forecasting highly uncertain. However, a comparison of anticipated clean power and transportation mineral requirements with current national consumption does provide helpful context (details for total minerals required in the two study scenarios appear in Tables 3—7). In general, material usage for clean technologies could add significantly to broader economy-wide demand.

For instance, total aluminum used in annually deployed EVs and power sector technologies could rival or exceed national annual aluminum production from both primary and recycled sources (currently 4,050,000 tons/year[6]). Similarly, copper usage in clean power technologies, transmission networks, and EVs could reach 1.1 to 1.6 million tons/yr, matching or exceeding current U.S. mining and recycled production of nearly 1.25 million tons in 2023.[7] And as previously alluded to, nickel usage in EV batteries and steel alloys for power sector projects could amount to double to triple current annual U.S. economy-wide nickel consumption (190,000 metric tons in 2023[8]). Use of other materials may be somewhat more modest, if still considerable. Future annual steel usage in clean electricity infrastructure and electric vehicles in our study grows to match 23-38% of current U.S. crude steel production (80.7 million metric tons in 2023.[9])

While solar-grade polysilicon is a manufactured feedstock and cannot be considered a critical mineral in any conventional sense, we note that domestic production of this commodity similarly may not suffice for meeting future U.S. needs. Annual solar-grade polysilicon use in deployed solar PV farms may reach 67,000 to 85,000 tons, relative to existing and announced U.S. solar-grade (or higher) polysilicon capacity of ~76,000 tons/yr—a supply chain that must serve both solar and semiconductor chip applications. The U.S. also currently has minimal existing solar PV cover glass manufacturing capacity, compared to projected annual usage of 735,000 to 1,422,000 tons/yr over the coming decades.

Table 3: Cumulative sum of minerals potentially required for U.S. power and road transportation sector decarbonization from 2025 to 2050 in two scenarios (left columns). Average future yearly mineral supplies required in the 2025-2035 and 2036-2050 time periods in two scenarios (right columns).

	NET-ZERO AMERICA	ADVANCING NUCLEAR ENERGY	NET-ZERO AMERICA		ADVANCING NUCLEAR ENERGY	
	Grand total (2025–2050)	Grand total (2025–2050)	Average yearly (2025–2035)	Average yearly (2036–2050)	Average yearly (2025–2035)	Average yearly (2036–2050)
Iron in steel	669,926,250	541,547,060	21,446,140	30,364,330	18,439,950	23,809,840
Sum of concrete	437,754,320	393,794,700	16,609,960	18,110,310	8,502,320	20,584,770
Non-steel iron	13,379,310	7,123,310	385,950	634,660	194,180	345,440
Sum of rare earths	274,880	219,800	8,370	12,750	7,620	9,580
Aluminum	106,408,380	99,068,650	3,548,350	4,728,320	3,381,720	4,350,100
Boron	12,960	5,340	480	540	180	230
Cadmium	11,530	7,350	650	340	480	170
Chromium	3,304,610	4,893,280	108,700	147,840	102,040	258,190
Cobalt	1,170,040	1,167,310	38,700	52,200	38,640	52,060
Copper	36,018,270	33,775,990	1,169,270	1,621,700	1,101,040	1,517,710
Glass and glass-reinforced plastic	7,508,180	4,713,230	372,950	251,910	278,610	128,470
Graphite	32,224,030	33,971,540	994,620	1,485,190	1,017,830	1,586,220
Lithium	3,215,110	3,358,420	100,520	147,320	102,430	155,610
Lead	134,050	145,320	4,340	6,040	4,530	6,670
Magnesium	509,430	336,110	16,840	22,740	13,600	13,340
Manganese	11,130,200	8,608,500	353,340	506,460	296,520	376,220
Molybdenum	2,880	5,410	100	120	110	280
Nickel	12,675,370	11,390,670	408,860	572,450	358,290	520,520
Niobium	0	730	0	0	10	40
Phosphate	8,834,870	9,503,680	264,980	412,340	273,890	450,990
Silicon, solar-grade	2,854,090	1,706,310	85,400	133,340	66,950	69,120
Silver	13,480	8,130	450	600	350	310
Solar PV cover glass	33,180,550	20,127,870	1,184,720	1,422,220	911,000	734,530
Tellurium	11,530	7,350	650	340	480	170
Tin	82,990	50,180	2,500	3,870	1,990	2,020
Titanium	122,600	49,910	3,680	5,720	2,140	1,900
Tungsten	0	1,830	0	0	20	110
Zinc	1,798,850	1,058,850	61,370	79,010	45,390	40,330

**all units in metric tons, rounded to the nearest 10 metric tons*

Table 4: Cumulative total minerals required for U.S. power sector decarbonization in the 2025-2035 and 2036-2050 time periods under the Princeton Net-Zero America E+ scenario (left columns) and the Breakthrough Institute Advancing Nuclear Energy Low Cost, Low Learning scenario (right columns).

CLEAN POWER GENERATION AND STORAGE				
	NET-ZERO AMERICA		ADVANCING NUCLEAR ENERGY	
	Total (2025–2035)	**Total (2036–2050)**	**Total (2025–2035)**	**Total (2036–2050)**
Iron in steel	76,855,470	179,210,450	46,793,600	80,893,130
Sum of concrete	166,099,630	271,654,690	85,023,200	308,771,500
Non-steel iron	3,859,450	9,519,860	1,941,760	5,181,550
Sum of rare earths	19,600	60,560	12,100	12,980
Aluminum	6,914,770	15,321,390	5,248,410	9,648,020
Boron	4,790	8,170	1,820	3,510
Cadmium	6,480	5,050	4,800	2,550
Chromium	557,670	1,147,290	491,040	2,802,590
Cobalt	1,270	2,980	620	890
Copper	2,275,420	5,541,200	1,593,080	3,981,270
Glass and glass-reinforced plastic	3,729,530	3,778,650	2,786,110	1,927,120
Graphite	140,460	2,450,440	372,530	3,965,880
Lithium	11,320	200,120	30,400	324,360
Lead	6,250	14,860	8,110	24,270
Magnesium	144,400	292,170	112,020	151,220
Manganese	1,455,270	3,409,280	887,120	1,455,730
Molybdenum	1,010	1,870	1,140	4,270
Nickel	1,399,690	3,149,630	893,990	2,370,640
Niobium	0	0	70	660
Phosphate	52,840	933,910	141,880	1,513,680
Silicon, solar-grade	854,010	2,000,080	669,520	1,036,790
Silver	4,520	8,970	3,500	4,640
Solar PV cover glass	11,847,210	21,333,340	9,109,970	11,017,900
Tellurium	6,480	5,050	4,800	2,550
Tin	24,960	58,030	19,880	30,300
Titanium	36,800	85,800	21,400	28,510
Tungsten	0	0	180	1,650
Zinc	601,740	1,160,680	441,950	580,470

**all units in metric tons, rounded to the nearest 10 metric tons*

Table 5: Average future yearly mineral supplies required for U.S. clean power generation and storage deployment in the 2025-2035 and 2036-2050 time periods under the Princeton Net-Zero America E+ scenario (left columns) and the Breakthrough Institute Advancing Nuclear Energy Low Cost, Low Learning scenario (right columns).

CLEAN POWER GENERATION AND STORAGE				
	NET-ZERO AMERICA		ADVANCING NUCLEAR ENERGY	
	Average yearly (2025–2035)	**Average yearly (2036–2050)**	**Average yearly (2025–2035)**	**Average yearly (2036–2050)**
Iron in steel	7,685,550	11,947,360	4,679,360	5,392,880
Sum of concrete	16,609,960	18,110,310	8,502,320	20,584,770
Non-steel iron	385,950	634,660	194,180	345,440
Sum of rare earths	1,960	4,040	1,210	870
Aluminum	691,480	1,021,430	524,840	643,200
Boron	480	540	180	230
Cadmium	650	340	480	170
Chromium	55,770	76,490	49,100	186,840
Cobalt	130	200	60	60
Copper	227,540	369,410	159,310	265,420
Glass and glass-reinforced plastic	372,950	251,910	278,610	128,470
Graphite	14,050	163,360	37,250	264,390
Lithium	1,130	13,340	3,040	21,620
Lead	630	990	810	1,620
Magnesium	14,440	19,480	11,200	10,080
Manganese	145,530	227,290	88,710	97,050
Molybdenum	100	120	110	280
Nickel	139,970	209,980	89,400	158,040
Niobium	0	0	10	40
Phosphate	5,280	62,260	14,190	100,910
Silicon, solar-grade	85,400	133,340	66,950	69,120
Silver	450	600	350	310
Solar PV cover glass	1,184,720	1,422,220	911,000	734,530
Tellurium	650	340	480	170
Tin	2,500	3,870	1,990	2,020
Titanium	3,680	5,720	2,140	1,900
Tungsten	0	0	20	110
Zinc	60,170	77,380	44,200	38,700

**all units in metric tons, rounded to the nearest 10 metric tons*

Table 6: Cumulative total minerals required for U.S. road electric vehicle deployment in the 2025-2035 and 2036-2050 time periods (left columns) and average future yearly mineral supplies required for U.S. EV deployment in the 2025-2035 and 2036-2050 time periods (right columns).

ELECTRIC ROAD TRANSPORTATION

	Total (2025–2035)	**Total (2036–2050)**	**Average yearly (2025–2035)**	**Average yearly (2036–2050)**
Iron in steel	113,756,440	231,879,930	11,375,640	15,458,660
Sum of rare earths	64,070	130,650	6,410	8,710
Aluminum	14,342,910	29,134,680	1,434,290	1,942,310
Chromium	529,330	1,070,320	52,930	71,350
Cobalt	385,770	780,030	38,580	52,000
Copper	7,444,100	15,113,050	744,410	1,007,540
Graphite	9,805,750	19,827,380	980,580	1,321,830
Lithium	993,930	2,009,730	99,390	133,980
Lead	37,160	75,780	3,720	5,050
Magnesium	23,980	48,890	2,400	3,260
Manganese	1,834,740	3,734,750	183,470	248,980
Nickel	2,688,950	5,437,090	268,890	362,470
Phosphate	2,596,980	5,251,140	259,700	350,080
Zinc	11,990	24,440	1,200	1,630

**all units in metric tons, rounded to the nearest 10 metric tons*

Table 7: Cumulative total minerals required for U.S. transmission infrastructure deployment in the 2025-2035 and 2036-2050 time periods (left columns) and average future yearly mineral supplies required for U.S. transmission infrastructure deployment in the 2025-2035 and 2036-2050 time periods (right columns).

ELECTRICITY TRANSMISSION

	Total (2025–2035)	**Total (2036–2050)**	**Average yearly (2025–2035)**	**Average yearly (2036–2050)**
Iron in steel	23,849,460	44,374,500	2,384,950	2,958,300
Aluminum	14,225,870	26,468,760	1,422,590	1,764,580
Copper	1,973,180	3,671,320	197,320	244,750
Manganese	243,360	452,800	24,340	30,190

**all units in metric tons, rounded to the nearest 10 metric tons*

Points of uncertainty

Where could this study be underestimating mineral demand?

- **Battery minerals.** Our calculations may somewhat underestimate battery mineral requirements, as our data primarily encompass cell-level materials and do not include some pack-level and balance-of-system mineral materials like battery casing or structures and grid connection in the case of grid storage systems.
- **Retirement and replacement.** Some stock of clean power, clean vehicle, and transmission units may reach end-of-life in coming years or decades and necessitate replacement, which this analysis does not consider. Even new deployment of some technologies like grid battery storage or electric vehicles over the next decade may require full replacement within the 2025-2050 period of analysis.
- **Sector coverage.** A focus on power and road transport sectors underestimates total U.S. energy transition mineral needs, as this analysis does not cover other clean technology sectors such as hydrogen technologies, residential appliances, non-road transportation, or carbon capture.
- **Export production.** If the U.S. succeeds in not only deploying clean technologies at home at large scales but also exports significant quantities of equipment through trade, such trends may further increase long-term mineral demands.
- **Model scope.** The assessed energy system modeling scenarios serving as the basis of this analysis do not cover Alaska, Hawaii, or U.S. territories and associated future infrastructure and EV deployment in these regions.

Where could this study be overestimating mineral demand?

- **Technological improvements.** Strong market and competitive incentives will continue to push equipment manufacturers to reduce the quantities of minerals used in technologies like solar panels and batteries, while also substituting cheaper and more available minerals where practical. Improving equipment performance will also reduce mineral needs, with clean energy platforms and batteries generating and storing more energy for the same amount of materials, while operating for longer lifetimes.
- **Lower electric vehicle adoption**. This analysis calculated electric vehicle mineral needs based on a Princeton Net-Zero America scenario assuming rapid large-scale electric vehicle adoption, with EVs representing 62% of new light automobile sales by 2030 and >90% of new sales by 2040 and reaching a figure of 313.5 million EVs in service by 2050. Slower growth in EV ownership would reduce battery mineral requirements.

- **Societal energy efficiency.** Innovations, operational improvements, and societal shifts that enable the same quantity of energy to accomplish more in the economy may also help moderate the scale of the future energy system.

What areas of uncertainty might work in either direction?

- **Technology coverage.** Within the power sector, this analysis does not consider additional material needs for some other low-carbon technologies like geothermal, hydropower, concentrating solar power, gas-fired power plants with carbon capture, or more exotic concepts like ocean thermal or fusion power. At the same time, such technologies could also fulfill more future energy demands than anticipated, eliminating some material demands associated with solar, wind, and batteries.
- **Demand.** Future energy demand or population growth may trend somewhat higher or lower than anticipated, affecting the total size of the national energy system. Depending on policy ambitions, deployment of low-carbon technologies may also take place more slowly than our scenarios assume.

We stress that our estimates simply represent raw material needs for future deployed U.S. clean technologies independent of any assumptions about whether those materials originate from domestic production or arrive as imports. Readers should not interpret the tonnages of minerals quantified here as national production goals, as the United States cannot and should not endeavor to supply all of its own energy transition raw materials with expanded domestic production.

Finally, recycling of end-of-life technologies as well as secondary production of metals like aluminum or steel using scrap from other sectors can provide a growing and promising supply of future energy transition minerals. Our study quantifies only absolute potential mineral requirements for power and road transport sector decarbonization, which some combination of new mined minerals and recycled production will ultimately help meet. The precise contribution of recycled materials to future supply requirements is uncertain, although intuition and other quantitative assessments suggest[10] that new mining will fulfill[11] the majority of projected future demand until around 2040[12] or later.

PRIORITIES FOR BUILDING SECURE MINERAL SUPPLY CHAINS FOR THE U.S.

Mining sector

The U.S. has two broad pathways to better secure raw mineral supplies for clean energy technology supply chains: expanding domestic production and leveraging trade with allies and other trade partners.

Domestic production

The potential growth of domestic mine production varies from mineral to mineral based on natural occurrences of geologic deposits (Table 8). Notably, the U.S. has particular capacity to expand domestic mine production of cobalt, lithium, nickel, platinum group elements, and rare earth elements due to the good potential of domestic reserves. These minerals offer particularly valuable priorities for domestic growth given insufficient existing production relative to likely future needs.

The battery graphite supply chain represents a somewhat special case. The U.S. currently does not mine natural graphite, and its relatively small domestic geological reserves suggest only limited potential to expand domestic production. However, recent exploration efforts show promise for at least modest production in Alabama and Alaska. Given that the U.S. would otherwise remain particularly dependent on Chinese imports for battery-grade graphite, U.S. policy efforts should adopt a multi-pronged approach, promoting further development of graphite projects in these regions while also exploring domestic production of synthetic graphite, domestic refining of graphite mined by overseas partners, and alternative sources of overseas graphite imports.

Table 8: Overview of U.S. potential for meaningful expansion of domestic mining for clean technology minerals, based on current production and reserves. Source: U.S. Geological Survey 2024 Mineral Commodity Summaries.[13] Potential alternative and unconventional sources for some minerals appear in the right column. Though this study did not specifically quantify future needs for gallium, germanium, and platinum group metals, this table includes these mineral supply chains due to their relevance in clean energy technologies.

MINERAL	POTENTIAL TO EXPAND DOMESTIC MINE PRODUCTION	ALTERNATIVE OPPORTUNITIES
Aluminum (i.e., bauxite)	low	n/a
Cadmium	low	enhanced recovery from zinc production
Chromium	low	n/a
Cobalt	high	deep sea nodules
Copper	medium	deep sea nodules, in-situ recovery
Gallium	low	recovery from aluminum (i.e., bauxite) and zinc production, coal fly ash
Germanium	low	enhanced recovery from zinc production
Graphite	low	synthetic production from coal or biomass feedstocks
Iron	medium	n/a
Lead	medium	n/a
Lithium	high	brine, solution mining
Magnesium	medium	brine, solution mining
Manganese	low	deep sea nodules
Molybdenum	high	n/a
Nickel	medium	deep sea nodules
Phosphate	medium	n/a
Platinum Group Elements	medium	enhanced recovery from nickel production
Rare Earth Elements	medium	recovery from coal fly ash, iron tailings, phosphate production
Silver	low	n/a
Tellurium	medium	enhanced recovery from copper production
Tin	low	n/a
Titanium	low	n/a
Zinc	low	n/a

In addition to expanding domestic mine production, novel technologies exist that may allow production of a number of minerals that either do not require conventional mining or make more efficient use of mining that already occurs. Federal research funding and agency programs should prioritize further research and development of these technologies:

- **Deep sea nodules**, which offer a new source of cobalt, copper, manganese, and nickel by collecting baseball-sized, metal-rich nuggets sitting atop the ocean floor.[14]
- **Byproduct recovery**, which allows extraction of additional minerals from existing operations or wastes. Examples include rare earth element production from coal fly ash, iron mine tailings, and phosphate ore, or gallium production from aluminum (i.e., bauxite) ore, zinc ore, and coal fly ash.[15,16,17,18,19]
- **Direct extraction technologies**, which allow chemical isolation of minerals like lithium from deep underground brines in a less water- and land-intensive method than using evaporation ponds.[20]
- **Synthetic graphite**, which enables production of synthetic battery-grade graphite from coal and biomass feedstocks that, while at higher-cost, yield higher-quality battery materials while reducing demand for mined natural graphite.[21,22]
- **In-situ recovery**, which entails pumping fluids through rock formations and back to the surface and thus can economically liberate metals with minimal excavation. This technology has proven application for uranium and promising potential for copper.[23]

Trade partnerships

The U.S. can partner with overseas mineral producers to compensate for limited viable domestic geologic reserves of some minerals, while generally diversifying its mineral supply chains through a combination of domestic production and imports (Table 9). Australia, Brazil, Canada, India, Kazakhstan, Mexico, Peru, South Africa, Turkey, and Vietnam stand out as broadly attractive potential trade partners given that each produces multiple clean energy technology minerals. Notably, the U.S. should emphasize trade partnerships with the specified countries to secure supplies of the following minerals due to particularly limited domestic reserves:

- **aluminum (i.e., bauxite)**—Australia, Brazil, Guinea, India, Indonesia
- **cadmium**—Canada, Japan, South Korea
- **chromium**—South Africa
- **gallium**—Japan, South Korea

- **germanium**—Belgium, Canada, Germany
- **graphite**—Brazil, Madagascar, Mozambique, South Korea
- **manganese**—Australia, Gabon, South Africa
- **tellurium**—Japan

Note that Brazil, Canada, Greenland, South Africa, and Tanzania report significant rare earth element reserves not captured in the table, but they currently conduct minimal mining. Our country supply analysis also considers that the following minerals are primarily recovered as byproducts of other minerals: cadmium (zinc), gallium (aluminum, zinc), germanium (zinc), and tellurium (copper). Should the U.S. invest in domestic processing capacity for these byproduct minerals, it could theoretically import raw ore feedstocks from countries producing the corresponding primary mineral. Similarly, the U.S. could source nickel ore as feedstock for platinum group metal production, even though platinum group minerals also occur independently.

Table 9: Summary of potential alternative suppliers of clean technology minerals, based on current production from mining. Source: U.S. Geological Survey 2024 Mineral Commodity Summaries.[24] Though our study did not specifically quantify future needs for gallium, germanium, and platinum group metals, this table includes these mineral supply chains due to their relevance in clean energy technologies.

MINERAL	MAJOR PRODUCERS	MINOR PRODUCERS
Aluminum (i.e., bauxite)	Australia, Brazil, Guinea, India, Indonesia	Greece, Jamaica, Kazakhstan, Turkey, Vietnam
Cadmium	Canada, Japan, South Korea	Australia, Bulgaria, Germany, Kazakhstan, Mexico, Netherlands, Norway, Peru, Poland
Chromium	South Africa	Finland, India, Kazakhstan, Turkey
Cobalt	Congo, Indonesia	Australia, Canada, Madagascar, New Caledonia (France), Papua New Guinea, Philippines, Turkey
Copper	Chile, Congo, Peru	Australia, Canada, Indonesia, Kazakhstan, Mexico, Poland, Zambia
Gallium	n/a	Germany, Hungary, Japan, Kazakhstan, South Korea, Ukraine
Germanium	n/a	Belgium, Canada, Germany
Graphite	Brazil, Madagascar, Mozambique, South Korea	Austria, Canada, Germany, India, Mexico, Norway, Sri Lanka, Tanzania, Turkey, Ukraine, Vietnam
Iron	Australia, Brazil, India	Canada, Chile, Kazakhstan, Mexico, Peru, South Africa, Sweden, Turkey, Ukraine
Lead	n/a	Australia, India, Mexico, Peru, Sweden, Turkey
Lithium	Australia, Chile	Argentina, Brazil, Canada, Portugal, Zimbabwe
Magnesium	Brazil, Turkey	Australia, Austria, Canada, Greece, India, Slovakia, Spain
Manganese	Australia, Gabon, South Africa	Brazil, Côte d'Ivoire, Ghana, India, Kazakhstan, Malaysia, Mexico, Ukraine, Vietnam
Molybdenum	Chile, Mexico, Peru	Armenia, Australia, Canada, South Korea, Mongolia
Nickel	Indonesia, Philippines	Australia, Brazil, Canada, New Caledonia (France)
Phosphate	Morocco	Australia, Brazil, India, Israel, Kazakhstan, Peru, South Africa, Vietnam
Platinum Group Elements	South Africa	Canada, Zimbabwe
Rare Earth Elements	Australia, Thailand	India, Madagascar, Vietnam
Silver	Mexico, Peru	Argentina, Australia, Bolivia, Chile, India, Kazakhstan, Poland
Tellurium	Japan	Canada, Sweden
Tin	Bolivia, Brazil, Congo, Indonesia, Peru	Australia, Laos, Malaysia, Nigeria, Vietnam
Titanium	Australia, Mozambique, South Africa	Canada, India, Kenya, Madagascar, Norway, Senegal, Sierra Leone, Ukraine, Vietnam
Zinc	Australia, Peru	Bolivia, India, Kazakhstan, Mexico, South Africa, Sweden

Mineral processing sector

Unlike mining, the processing segment of the mineral supply chain, such as smelting and refining, need not be co-located with geologic mineral deposits. This situation creates some potential for the U.S. to expand processing capacity to meet manufacturing needs independent of its geologic mineral resources (Table 10). In some cases, the domestic processing industry can build upon existing capacity and expertise to scale up, but can only expect to supply a limited fraction of processing feedstocks from domestic mine production and would therefore need to establish international supply arrangements to maximally utilize expanded processing capacity.

Priority mineral processing sectors

The U.S. should emphasize expanding domestic processing capacity for cobalt, gallium, germanium, graphite, lithium, nickel, and rare earth elements given minimal existing industry presence.

In particular, graphite stands out as the top priority. In a concession to U.S. automakers, the Biden administration's EV tax credit guidance and newly-announced tariffs have left a two-year grace period before imposing harsher conditions on imported battery graphite materials. However, this two-year pause has weakened the near-term domestic market demand signal for domestic content credit-eligible graphite even as global graphite prices slump in response to Chinese overcapacity. Providing greater price stability for domestically mined graphite would help ensure nascent graphite projects move forward in time to guarantee more adequate domestic supply once the grace periods for tariffs and domestic content expire. Policy mechanisms that could potentially achieve this stability include a physical mineral reserve or stockpile program that covers graphite, financial forward contracts like contract-for-differences, or offtake backstop agreements that provide some certainty of compensation or sold product during price crash events.

A number of graphite processing projects in the United States are entering production, while other mine and processing plant projects are engaged in early planning, possibly amounting to around 200,000 tons of annual production by the late 2020s in an extreme best-case scenario.[25,26,27,28,29,30,31] However, the success of many of these projects remains uncertain, particularly given long mine permitting timescales. Furthermore, by our calculations, even this optimistic figure for annual production may equal only 1/4th to 1/6th of the battery graphite potentially deployed yearly in U.S. EVs and grid storage facilities in the 2025-2050 period.

Table 10: Assessment of currently operating or proposed domestic processing capacity for various clean technology minerals. Processing statuses describe domestic processing capacity relative to other countries (minimal, nominal, moderate, competitive), while recycling statuses describe domestic recycling production relative to both domestic and overseas processing capacities (minimal, moderate, significant).

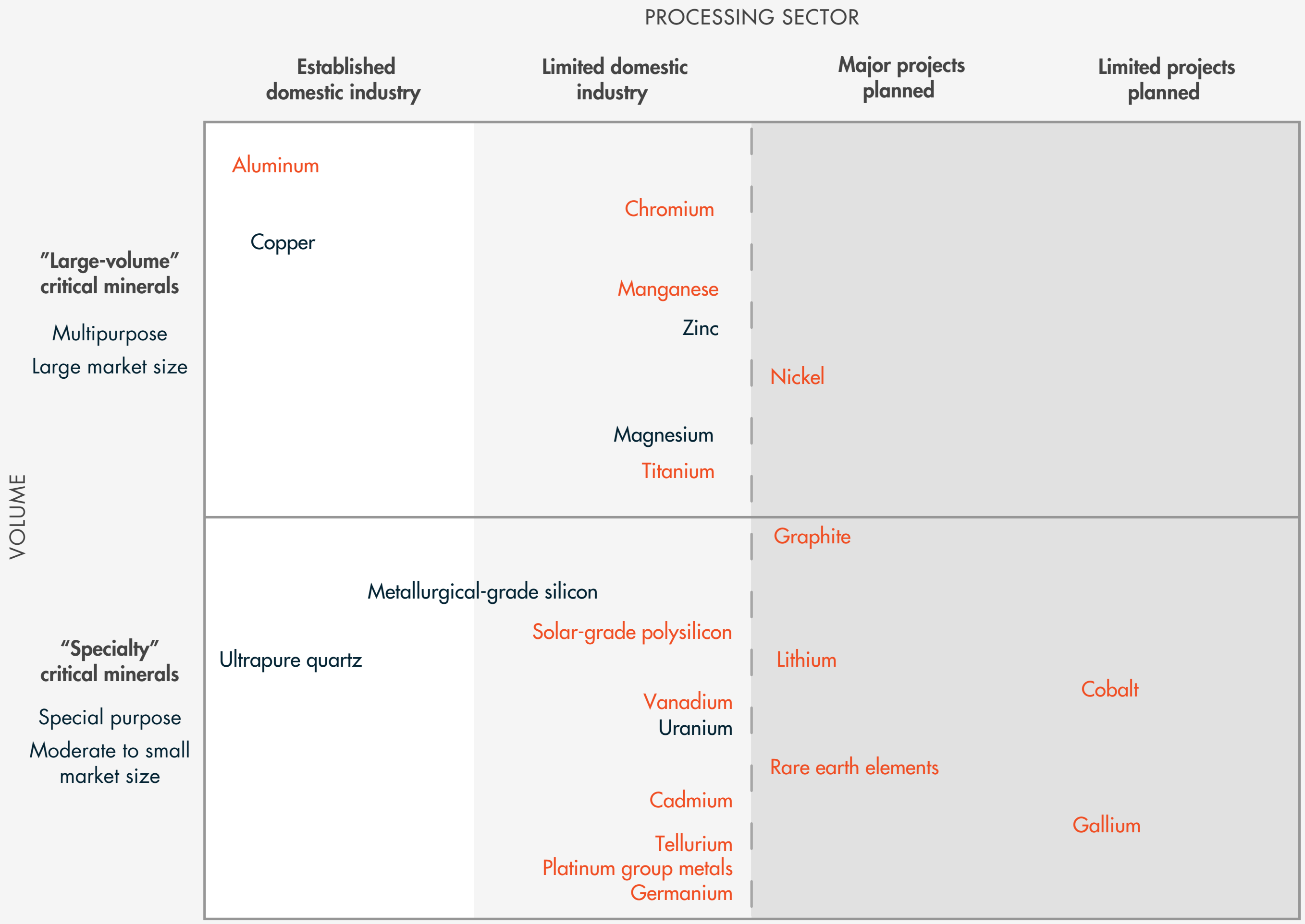
MINERAL	STATUS
Aluminum	Minimal alumina capacity (aluminum precursor) and moderate primary aluminum capacity both relying on imports for a significant portion of feedstock. Significant secondary production from recycled scrap.
Cadmium	Nominal primary capacity as a byproduct of zinc refining. Minimal secondary production from recycled scrap.
Chromium	Minimal primary capacity for the chemical sector and moderate primary capacity for the alloy sector, both relying on imports for a significant amount of feedstock. Minimal secondary production from recycled scrap.
Cobalt	No primary capacity, but companies have proposed new facilities in Arizona, Missouri, North Dakota, and Oklahoma. Moderate secondary production from recycled scrap.
Copper	Competitive primary capacity, relying on imports for only a limited amount of feedstock. Minimal secondary production from recycled scrap.
Gallium	Minimal primary refining capacity. Moderate secondary production from recycled scrap.
Germanium	Minimal primary capacity. Minimal secondary production from recycled scrap.
Graphite	No primary capacity for natural graphite, but companies have proposed new facilities in Alabama, Alaska, Louisiana, and Washington.
Iron	Moderate primary capacity, relying on imports for only a limited amount of feedstock. Moderate secondary production from recycled scrap.
Lead	No primary capacity. Significant secondary production from recycled scrap.
Lithium	Minimal capacity, but companies have proposed new facilities in Arkansas, Nevada, North Carolina, Oklahoma, South Carolina, Tennessee, and Texas.
Magnesium	Moderate primary capacity for the chemical sector and competitive primary capacity for the alloy sector, both relying on imports for only a limited amount of feedstock. Significant secondary production from recycled scrap.
Manganese	Moderate capacity for both the chemical and alloy sectors, both relying on imports for a significant amount of feedstock.
Molybdenum	Moderate primary capacity relying on imports for only a limited amount of feedstock. Moderate secondary production from recycled scrap.
Nickel	No primary capacity, but companies have proposed new facilities in Missouri, North Dakota, Oklahoma, and Texas. Moderate secondary production from recycled scrap.
Platinum Group Elements	Competitive primary processing capacity. Significant secondary production from recycled scrap.
Rare Earth Elements	Minimal capacity, but companies have proposed new facilities in Colorado, Texas, and Wyoming.
Silver	Competitive primary capacity relying on imports for a moderate amount of feedstock. Moderate secondary production from recycled scrap.
Tellurium	Nominal capacity as a byproduct of copper refining.
Tin	No primary smelting capacity and minimal primary refining capacity, relying on imports for a significant amount of feedstock. Moderate secondary production from recycled scrap.
Titanium	Competitive chemical sector capacity and moderate alloy sector capacity, both relying on imports for a significant amount of feedstock. Minimal secondary production from recycled scrap.
Zinc	Moderate primary capacity relying on imports for only a limited amount of feedstock. Moderate secondary production from recycled scrap.

Source: *U.S. Geological Survey 2024 Mineral Commodity Summaries and corresponding Mineral Yearbooks from the National Minerals Information Center.*[32,33] *This table includes gallium, germanium, and platinum group metals due to their relevance in clean energy technology even though our quantitative estimates did not account for these minerals.*

Policy support tools

Financial support for processing should prioritize minerals with limited existing domestic capacity as novel markets face higher risks than industries with existing domestic expertise. It should also prioritize smaller market volumes since policy support may become impractically costly for commodities with larger trade flows (Figure 3).

Figure 3: Conceptual illustration organizing critical minerals for clean energy technologies based on existing U.S. domestic processing capacity, market volume, and breadth of market applications. Minerals in red indicate high vulnerability to Chinese mineral market price volatility. Note that magnesium and metallurgical-grade silicon are insulated from Chinese market dynamics via import tariffs. Illustration includes some minerals not considered in our quantitative estimates.



Price supports are a type of financial support tool that distributes payments to facilities when commodity prices fall low enough to otherwise close operations. In addition to the criteria listed in the previous paragraph, policymakers should give preference to minerals with minimal potential for substitution and high vulnerability to Chinese market dynamics. Given these considerations, price supports could most meaningfully benefit graphite, lithium, rare earth elements, cadmium, gallium, tellurium, germanium, and nickel. Platinum group elements also face volatility risk that warrants price support, given the concentration of platinum group metal production in just a handful of countries, including South Africa and Russia.

Many clean energy minerals suffer from a lack of liquidity since they constitute small, emerging markets with relatively few participants.[34,35] Policymakers could establish a program that creates physical stockpiles of these minerals to function as a commodity exchange. Such an exchange would offer producers more options to find buyers beyond long-term offtake agreements, which in turn would hedge risk and encourage investment in domestic facilities. Likewise, greater liquidity would alleviate price volatility by encouraging participation from traders and investment institutions. Beyond private sector participation, a stockpiling program could also stabilize prices through its purchases and sales, taking supply off the market during gluts and reintroducing it when prices recover.

Federal grant awards and loan guarantees are readily accessible forms of financial support that alleviate capital and operating cost barriers. These tools can help lower entry barriers for emerging industries like electrolytic magnesium, platinum group metals, and cobalt. Alternatively, established industries like copper and aluminum could benefit from increased processing yields allowed by funded facility upgrades and improvements. Projects that process ores containing gallium, germanium, tellurium, cadmium, and cobalt present a uniquely valuable target for grants and loans as these minerals occur as byproducts of other minerals and could increase supply without increasing mining activity.

Meanwhile, direct production tax credits for domestic critical minerals extraction would create a strong market incentive by improving project economics across the mining sector. Policymakers could also provide funding for new processing projects to conduct site selection studies similar to those executed by the Department of Defense under the Defense Production Act.[36] Such studies would optimize project feasibility by considering factors like environmental sensitivity, project costs, and available state and local incentives, capitalizing on the ability to site mineral processing facilities more flexibly than mining projects.

The recently introduced Global Strategy for Securing Critical Minerals Act of 2024[37] would advance multiple support mechanisms including expertise-sharing across partner countries, financial support for new and existing domestic processing, refining, and recycling facilities, and financial support for domestic manufacturers to secure overseas mineral supplies.

Ultimately, effective support for mineral supply chain expansion may, as two proposals have suggested, require a federal program or government agency authorized to employ multiple support mechanisms, with the flexibility to apply different measures to different mineral markets as appropriate.[38,39] Such an approach could allow policy support strategies to adapt over time as market conditions change and industries evolve, even relaxing support as markets achieve stability.

While commercial harvesting of seafloor minerals may still be years away, Congress and/or the Treasury Department should also proactively classify international seabed minerals arriving first at U.S. ports as domestic content. Seafloor polymetallic nodules in particular have the potential to markedly alter global supply chains for nickel, manganese, copper, and cobalt while reducing future terrestrial mineral excavation.[40] However, the domestic content criteria do not currently define how such minerals might be considered for eligibility, rendering them by default non-eligible to count toward domestic content eligibility calculations. A regulatory clarification would incentivize future seafloor nodule collection operations to consider U.S. facilities for processing harvested nickel, manganese, copper, and cobalt.[41]

Finally, trade policies offer useful levers for leveling the playing field for domestic mineral supply chain operations by helping internalize or mitigate the effects of environmental pollution, abusive labor practices, and commodity market manipulation. Of course, tariffs already play a useful role in insulating U.S. industries like magnesium and metallurgical-grade silicon from market manipulation by rival producers overseas. Targeted mechanisms such as carbon border adjustments as recommended by the proposed Foreign Pollution Fee Act[42] could help establish a market advantage for U.S. producers whose products boast a lower environmental footprint. Also, imposing strict ethical and transparency standards on imported mineral products would force irresponsible overseas producers to either bear the cost of reforming their production practices or lose U.S. market access.

Many of the policy tools discussed here would alleviate market-related burdens. Yet, more efficient permitting could also encourage growth by shortening project lead times and lowering costs while maintaining strong environmental standards. Proposals like the Energy Permitting Reform Act of 2024[43] work toward these goals for renewable energy projects, by, for example, expanding categorical exclusions that streamline permitting of low-impact activities—one of many ideas that policymakers could similarly extend to the mineral sector. This bill does include some mining-related provisions like judicial review limits to discourage baseless lawsuits and revisions to how mine operators claim federal land for supporting mill infrastructure, allowing more flexibility in planning operations. Increasing funding for staffing at state environmental agencies would also accelerate permit reviews since states often administer Environmental Protection Agency permits that processing facilities require.

CONCLUSION

Fundamentally, eliminating carbon emissions from the power and road transportation sectors requires roughly doubling nationwide electricity generation while replacing much of the entire existing U.S. road vehicle fleet. Such a vast redesign of the country's electricity and automobile sectors will necessarily mobilize large quantities of raw material.

The rise of new energy technologies and electric vehicles is too important a U.S. economic and strategic priority to entrust to today's highly concentrated supply chains dominated by a handful of countries. At the same time, market dynamics and practical limits mean that fully replicating such commodity chains anew remains neither desirable nor achievable. Rather, government and industry should strive to diversify mineral supply chains and thus insulate energy technology leadership efforts from economic disruption and geopolitical volatility.

To accomplish this, the U.S. will need to meet more of its mineral needs through a combination of expanded domestic production and close cooperation with allies and other trade partners. To increase production, policies can aim to encourage traditional mine development and mineral processing as well as innovative approaches for producing metals with a smaller or minimal environmental footprint. At the same time, our country should seek to develop a recycling sector that is prepared to both process end-of-life products at an economy-wide scale by the mid-2030s and to expand in magnitude alongside energy transition efforts.

These efforts will promote better conditions for national success in key future economic growth sectors like batteries, electric vehicles, and new energy technologies. Meanwhile, robust U.S. mineral supply chain strategies will also create valuable new economic opportunities of their own in the mining, heavy industry, and recycling sectors. With an improved quantitative sense of future U.S. mineral usage in the clean technology space, the U.S. can advance towards the future with a more confident grasp of national mineral supply priorities and how to better meet them.

APPENDIX: METHODOLOGY

Scenario design

Our analysis performed a first-order approximation of the volume of minerals potentially required, annually and in total, to support ongoing U.S. decarbonization efforts in the electricity and road transportation sectors between 2025 and 2050. We adopted a simple approach of multiplying projected future deployment of technologies like wind, solar, nuclear, batteries, and electric vehicles with material intensity data per unit of technology.

For power sector mineral needs, we considered two illustrative scenarios based on published modeling studies, both of which assessed potential evolutions in the U.S. electricity system between the present and 2050:

- **A high-renewables pathway**—the Princeton Net-Zero America study's E+ scenario.
- **A balanced renewables and nuclear pathway**—the Breakthrough Institute's Advancing Nuclear Energy study's Low Cost, Low Learning scenario.

For road transportation and transmission network mineral requirements, we evaluated only a single scenario for future EV adoption and transmission network expansion based on the Princeton Net-Zero America modeling. We then added these mineral consumption values to both of the above cases in our assessment of total demands.

Given large uncertainties around changing technologies, mineral efficiency improvements and substitution, and future demand trends in each technology category, our results are almost certain to diverge from mineral demands in practice. However, we are confident that our study estimated the correct order of magnitude of national mineral requirements for power and road transport sector shifts over the coming decades, while providing a basis for subsequent work to refine our results.

As our analysis assessed the electricity and road transportation sectors only, our calculations likely underestimate real future total energy transition mineral demands. Other sectors like hydrogen technologies and infrastructure (electrolyzers, fuel cells, pipelines), residential appliances (heat pumps, electric furnaces and water heaters, home EV chargers), non-road transportation (electric non-road utility vehicles, aircraft, ships and ferries), and carbon capture (CO_2 capture equipment, pipelines) will likely drive considerable mineral consumption of their own. While these demand drivers may prove secondary in magnitude relative to future power sector and road transportation needs, neither are they negligible from a supply perspective—particularly in the case of specialty metals like platinum group metals used in hydrogen electrolyzers and fuel cells.[44]

Electricity sector mineral requirements

Generation and storage

To calculate mineral needs per unit of electricity generation and storage technology, we leveraged findings from our previously published report *Updated Mining Footprints and Raw Material Needs for Clean Energy*.[45] This report presented mineral requirements per GW of nameplate capacity for utility-scale solar, wind, and nuclear generation technologies, while also quantifying some mineral inputs per GWh of utility-scale lithium-ion battery storage capacity. Using these requirements somewhat underestimated battery storage mineral needs, as these prior results encompassed cell-level mineral inputs only and did not include pack-level or balance-of-system mineral needs.

Using our same previous methodology to adapt solar and wind farm mineral usage values from the National Renewable Energy Laboratory's Renewable Energy Materials Properties Database (https://apps.openei.org/REMPD/), we also added mineral requirements for rooftop residential crystalline silicon solar, rooftop commercial crystalline silicon solar, and cadmium-telluride thin-film solar photovoltaic systems to our dataset. Following our previous approach, we corrected the rooftop residential and commercial crystalline silicon solar material intensity data for solar PV cover glass, silver, and solar-grade polysilicon based on more up-to-date industry information.

We assumed that all new advanced nuclear power plants possess a mineral requirement identical to our previous literature-based estimate for the General Electric Hitachi BWRX-300, a light-water small modular reactor design. These values may overestimate nuclear sector mineral demands. Conventional large light-water reactor designs like the Westinghouse AP-1000 would boast reduced mineral needs in comparison to the BWRX-300, as might alternative advanced nuclear power plant designs.

To quantify total future material needs for each technology, we calculated growth based on future installed solar, wind, nuclear, and utility-scale battery capacity projections by 2035 and by 2050 for the Princeton Net-Zero America study's E+ scenario and the Breakthrough Institute's Advancing Nuclear Energy study's Low Cost, Low Learning scenario, relative to currently deployed capacity in 2024 largely as assessed by the U.S. Energy Information Administration,[46] leveraging the *Global Offshore Wind Report 2024*[47] in the case of offshore wind. This approach, importantly, does not consider retirement and replacement of either existing or future power sector generation and storage infrastructure, which would modestly increase mineral needs relative to our first-order calculation.

In brief, both scenarios assumed considerable growth in U.S. electricity generation from the current ~4,000 terawatt-hours (TWh) in 2020 to 9,825 TWh in 2050 under the Net-Zero America's E+ scenario and 7,511 TWh in 2050 for the Advancing Nuclear Energy Low Cost, Low Learning scenario. The Net-Zero America scenario deploys significantly more wind and solar capacity, whereas the Advancing Nuclear

Energy case generates ~40% of U.S. electricity from nuclear power in 2050 while also deploying more battery storage. Although the future U.S. electricity system is likely to differ from both of these scenarios in practice, our contrast of an ambitiously high-renewables case with an ambitiously high-nuclear case likely bounds power sector mineral demands.

We assigned crystalline silicon solar PV a market share of 75% of all U.S. utility solar for 2025 to 2035, increasing to 90% of utility solar for the following 2036-2050 period. The remainder of utility-scale solar PV consists of cadmium telluride thin-film solar PV installations. We assumed commercial solar PV systems account for 34% of distributed solar deployment, with residential solar PV comprising the remaining 66%.

Transmission

Using a current high-voltage transmission grid size estimated at 1,033,199 km (642,000 miles),[48] we applied REPEAT's net zero pathway annual transmission growth rate of 2.4%[49] to approximate the annual high-voltage grid size until 2050. We adapted the approach in Equation 3 of Deetman et al.[50] to roughly estimate the length of the U.S. medium-voltage and low-voltage transmission networks as well as the amounts of steel, aluminum, and copper required to support annual growth of the grid. This equation calculates and sums the total required grid materials for transmission lines, transformers, and substations. See our Supplementary Files for our assumed material intensity and unit frequency constants, including parameters used for the same calculations for medium- and low-voltage lines. The sum of material requirements for each annual iteration of transmission grid growth yielded the total materials required for grid expansion in 2025-2035 and 2036-2050.

Our investigation of transmission network minerals employed only a rough estimation of low-voltage and medium-voltage network size below 135 kV and associated infrastructure. It thus likely represents a relatively imprecise estimate of mineral needs for the low-voltage and medium-voltage categories.

Most steel in transmission infrastructure consists of carbon steel (98-99% iron by mass) galvanized with an iron-zinc layer[51] for corrosion resistance. We therefore assumed that steel in transmission and distribution networks consists of 98% iron and 1% manganese by mass,[52] omitting all other minor, non-critical mineral alloy constituents. As zinc usage in galvanized coatings is difficult to estimate, our analysis did not consider zinc demands in transmission networks, noting that associated zinc consumption may be significant. This assumption may underestimate consumption of some alloy constituents like chromium, nickel, and manganese in stainless, electrical, or specialty steels used in transformers and substations, while overestimating iron requirements. Note also that some aluminum conductors for specific applications and environments include magnesium as a minor alloy constituent, but we were not able to quantify the extent of such usage nationwide.

Road transportation sector mineral requirements

Road transportation mineral requirements account for the number of light-duty, medium-duty, and heavy-duty battery electric vehicles deployed in the Princeton Net-Zero America study's E+ scenario.[53] Our mineral requirement estimates assumed that light-, medium-, and heavy-duty vehicle characteristics match those of the Federal Highway Administration[54] as defined by gross vehicle weight. Future growth in light-duty vehicles accounted for the currently operating stock of EVs,[55] but assumed negligible present deployment of medium- and heavy-duty EVs. Vehicle numbers assumed no retirement over the scenario's time period, thereby underestimating total mineral requirements.

We based vehicle glider and motor mineral requirements on compositions detailed in Fishman et al.[56] for a representative light-duty vehicle. Note that these compositions disregard minor amounts of metals used in miscellaneous systems like electric window components or interior fixtures. Medium-[57] and heavy-duty[58] vehicle glider and motor materials represent the light-duty composition scaled to the curb weights of representative models of each class.

We based battery mineral requirements on those assumed in Woodley et al.[59] for a 75 kWh battery weighted to reflect anticipated 2032 market proportions of NMC-111 (0.8%), NMC-523 (1.5%), NMC-622 (11.3%), NMC-811 (10.2%), NCA (15.8%), and LFP (60%) sales. We assumed the steel reported for each battery type was SAE 304 type steel and disregarded the silicon, sulfur, nitrogen, phosphorus, and carbon contents as negligible. This accounting may not fully cover pack or module-level components for battery systems other than steel, further underestimating some structural battery metal requirements. We assigned the 75 kWh battery to the light-duty class and scaled its composition accordingly to account for the 200 kWh battery used in the above medium-duty[60] model and the 400 kWh battery used in the above heavy-duty[61] model.

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