INTEGRATED SUMMARY:

ENERGY AND CRITICAL MATERIALS

Battery material supply issues could have negative impacts on the same order of magnitude as the semiconductor shortage on US vehicle prices, consumers, and workers as early as 2030. Vulnerability to lithium and cobalt supply shocks can be avoided with supply chain diversification and increased adoption of cobalt-free batteries.

Type of critical technology assessment Emerging product for which loss of access would have high social and economic impacts (and possibly security impacts)

Lead performers Elsa Olivetti, Kate S. Whitefoot

Program management Team two previously unconnected performers

Methods Industrial organization modeling, scenario modeling, supply chain modeling, engineering-economic models

Data Global mine supply data from S&P; historic data on material demand, prices, mining production, and mining costs; design, process, production, and labor hour data collected from private firms and published by Argonne National Laboratory; data on the top firms in the automotive market from Ward's

Criticality dimensions measured Economic well-being (consumer surplus losses, jobs)

Challenges for future critical technology assessment Need to bring together scholars with industrial organization and engineering analytic (technoeconomic) expertise, and make policymakers aware of the possibilities of such analysis and cobalt-free battery chemistries.

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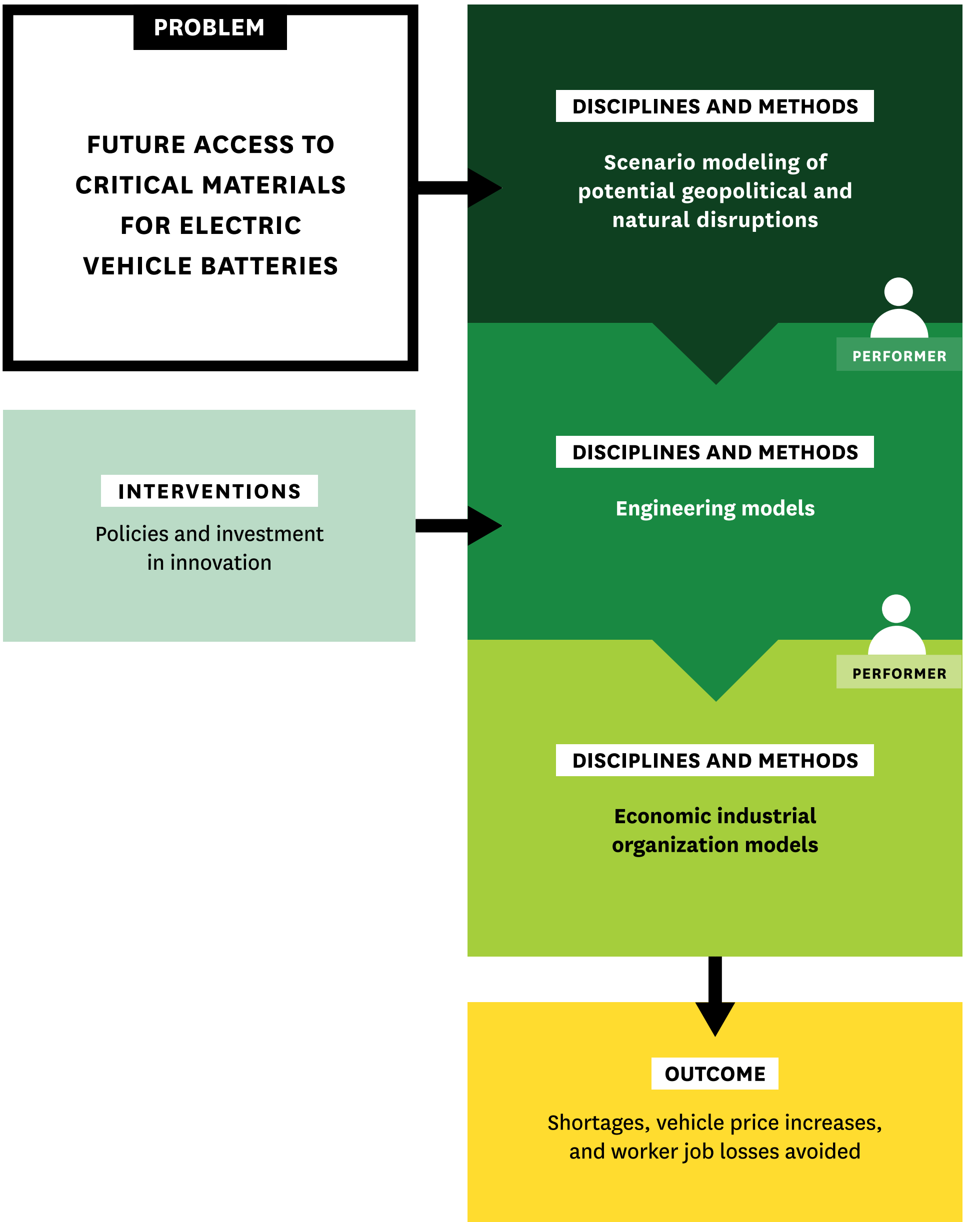
ENERGY AND CRITICAL MATERIALS

Combination of disciplines, methods produce novel findings



ENERGY AND CRITICAL MATERIALS

FINDINGS: Battery material supply issues could substantially increase US vehicle prices, harm consumers, and reduce manufacturing labor hours as early as 2030. Simulations of 2030 scenarios show that shocks to either lithium or cobalt can lead to increases in average US new vehicle prices (both conventional and electric vehicles) by about $1,100–$2,700 (2023 USD); 500,000–900,000 US households unable to purchase a new vehicle; consumer surplus losses of approximately $24 billion; and 20,700–37,400 labor-months of lost wages for battery cell and pack production line workers.

Unlike lithium and cobalt, graphite shortages (e.g., due to trade disputes) can be more easily mitigated by substitution of synthetic graphite in anodes. We estimate that this substitution would double the price of the input material but, compared to the lithium and cobalt scenarios, have a relatively low impact on battery production and US consumers.

RECOMMENDATIONS: Vulnerabilities to lithium and cobalt supply shocks can be avoided with supply chain diversification and increased adoption of cobalt-free batteries. Simulations suggest that encouraging additional supply of lithium domestically or in locations with lower risk of trade restrictions will mitigate the negative impacts of the modeled trade dispute scenario. Increasing the use of cobalt-free batteries (such as lithium-iron-phosphate) in the large majority of battery electric vehicle sales significantly reduces the negative impacts of the modeled cobalt supply shock scenario. Immediate alternatives exist to increase supply of lithium and for cobalt-free batteries, and increases in lithium supply and cobalt-free batteries could be further accelerated through investments in innovations in novel lithium processing.

Research Questions

What would be the impact of future battery material supply issues on the US automotive industry, consumers, and manufacturing jobs? What potential actions could mitigate these supply issues?

Motivation/Framing

The necessary electrification of the automotive industry will require attention to battery material supply chains. The location and ownership of some of these supply chains are concentrated in a limited number of countries, increasing risk of exposure to trade or other political disputes, natural disasters, and labor strikes. US vulnerability to these risks can be avoided if efforts are taken to enhance the resilience of materials supply and of industry to shocks or delays in expanding supply. A better understanding of how to build this resilience requires quantifying the impacts of material supply shocks and delays on the US automotive industry, consumers, labor, and vehicle production. This analysis identifies future scenarios that would negatively impact battery material supply, quantifies the expected material price increase, and estimates the impact of the price increase on US consumers and automotive manufacturing. We also discuss measures that could reduce the impacts of these scenarios.

Methods and Sources of Data

The modeling combines (i) interviews and literature review to form scenarios grounded in current mining concerns and historical mineral supply disruptions, (ii) global material supply and demand curves constructed using estimates of projected mine capacities, and (iii) simulations of the US automotive market using an oligopolistic equilibrium model. Our materials supply and demand models build on work by the Olivetti Group (Ryter et al. 2022) and the Materials Systems Lab (Bhuwalka et al. 2022) at MIT that uses global mine supply data from S&P.[1] Using historic data on material demand, prices, mining production, and mining costs, we generate future demand and supply curves for each of the at-risk critical materials to determine their marginal price under supply reduction scenarios developed from historic context and interviews with automakers, material and mining companies, and mineral resource experts. The scenarios chosen were deemed of higher probability, compared to other potential scenarios suggested in the expert interviews, but the experts did not identify a quantified probability of likelihood for any specific scenario.

Under the baseline scenario without disruptions, the mining supply matches the projected demand. When supply disruptions occur, the supply curve is modified according to the defined scenario and a new price is estimated based on the supply-demand equilibrium after accounting for the short-run price elasticity of supply and demand. For each scenario that we model, the estimated mineral prices are translated to input battery material costs (e.g., for NMC, LFP, and NCA battery chemistries[2]) using established cost models (Hsieh et al. 2019, Wentker et al. 2019), and we use the BatPaC (version 5.0) model to determine the resulting battery electric vehicle (BEV) battery pack production costs. We calculate (from Cotterman et al. 2022) the labor hours required to produce each battery pack. The automotive market model estimates how increases in battery production costs in each of the material supply scenarios will affect vehicle prices and production quantities. Specifically, we use a partial-equilibrium model of the US vehicle market where the top 17 automakers set vehicle prices to maximize profit while facing production capacity constraints on how much they can increase production of internal combustion engine (ICE) vehicles to counteract rising BEV production costs. This approach represents the short-term (i.e., 1- to 2-year) impact of the material supply scenarios before suppliers and automakers are able to alter production plans or supply chains in response to the material price increases. Details are provided in the supporting information available on the NNCTA website (nncta.org).

Integrative Findings

BATTERY MATERIAL SUPPLY CHAIN SCENARIOS

Table 4-3 lists the scenarios identified in interviews as plausible future conditions (between 2030 and 2040) that would affect battery material supply. These scenarios focus on supply chains for chemicals in the active materials for batteries, including lithium, nickel, cobalt, and graphite. Manganese, another such constituent, was not included in our scenarios as experts did not express concern about supply challenges in manganese-derived compounds. While manganese does face geographic concentration in processing the electrolytic form needed in batteries, the element is relatively inexpensive and mining reserves are globally abundant. Phosphorus and iron are also common active battery constituents that do not face notable availability concerns, although phosphorus warrants brief comment because of its application in LFP chemistries. Global phosphate reserves are not going to be depleted, but there may be concern about the regional availability of phosphorus for fertilizer manufacture, which could lead to food security concerns, particularly in high-population countries (such as India and Brazil) that depend on a few phosphorus-rich producing countries (Cooper et al. 2011). In addition, harmful impacts associated with the release of phosphorus into the environment call for careful attention (Penuelas et al. 2020).

In terms of scope, our quantitative scenarios focused on negative disruptions to supply; we did not quantify the impacts of increased supply or quantify shifts in demand, instead we qualitatively discuss potential mitigation measures.

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1 S&P Global Market Intelligence, https://www.spglobal.com/marketintelligence/en/campaigns/metals-mining#snl-metals-mining

2 NMC = nickel-manganese-cobalt; LFP = lithium-iron-phosphate; NCA = nickel-cobalt-aluminum

Scenario		Quantity	Estimated resulting median material price (2023 USD)	Estimated NMC811 battery production cost (2023 USD)
Lithium	Baseline	2.8 Mt	$20,000/t LCE	$99/kWh
	PRC lithium export *restriction* causes 15% refined supply reduction	2.58 Mt	$80,000/t LCE	$126/kWh
	US lithium mine *delay* causes 250 kt raw lithium supply *shortage*	2.7 Mt	$40,000/t LCE	$108/kWh
Nickel*	Baseline	3.2 Mt	$20,000/t	$99/kWh
	Declining ore grades cause 800 kt raw supply *reduction*	2.4 Mt	$88,457/t	$138/kWh
Cobalt	Baseline	302 kt	$49,280/t	$99/kWh
	Human rights abuses cause 14% raw cobalt supply *reduction* to US	274 kt	$199,360/t	$110/kWh
	Natural disasters in the DRC cause 65 kt global raw cobalt supply *reduction*	258 kt	$479,360/t	$126/kWh
Graphite	Baseline	-	$10/kg	$99/kWh
	PRC export *restrictions* create significant reduction in natural graphite supply	-	$20/kg	$109/kWh

*Nickel scenarios are in 2040 because the foreseen supply gap forms in the longer run.

TABLE 4-3. Price and quantity impacts of electric vehicle battery material supply scenarios in 2030. DRC = Democratic Republic of the Congo; LCE = lithium carbonate equivalent; NMC = nickel-manganese-cobalt; PRC = People's Republic of China. To help contextualize the price impacts of these scenarios: S&P Market Intelligence monthly price data from 2010–23 show that cobalt has ranged from $22,000/t to $94,000/t, lithium has ranged from $5,000/t to $80,000/t, and nickel has ranged from $8,000/t to $32,000/t.

Each scenario is modeled individually. Due to the nonlinear nature of metal supply curves, we anticipate that multiple disruptions would increase the magnitude of impacts on the battery market, making the scenarios more dire. These impacts could be estimated in future work to understand how the nonlinearities would interact with each other under multiple scenarios.

These conditions are based on historical supply disruptions and current supply concerns, which provide bounds on the values proposed in the scenarios. We describe them below in the order of their estimated impact on the costs of a 100 kWh NMC-811 BEV cathode and anode as a reference. These scenarios represent those that are currently anticipated; unanticipated disruptions may also occur, and in those cases the scenarios are proxies for disruptions that would have a similar magnitude impact on the quantity of mineral supplies listed.

DECLINING ORE GRADES CAUSE 800 KT NICKEL SUPPLY SHORTAGE

Industry reports expect an 800 kt supply gap to form in the nickel market between the 2200 kt of nickel sulfate available and the 3000 kt demanded (Fraser et al. 2021). This gap is due to declining nickel ore grades and the energy-intensive and more expensive process required to refine battery-grade nickel from laterite mines. Since nickel sulfide (the historic source of battery-grade nickel) ore grades have been declining, nickel laterites will be the main source of battery-grade nickel sulfate in the future. However, the two processes to convert laterites to battery-grade "class 1" nickel, high-pressure acid leaching (HPAL) and conversion of nickel pig iron (NPI) to matte, are costly and have negative environmental impacts. The carbon emissions released in HPAL are double those of the current process of converting sulfides to class 1 nickel and HPAL also involves negative environmental impacts from tailings disposal (IEA 2021, pp. 70–71). Moreover, capital costs for HPAL projects are typically more than double those for conventional smelters for oxide ore. The NPI-to-matte route is very energy-intensive, which leads to high energy costs and carbon emissions over 5 times larger than those of sulfide refining. The higher economic and environmental costs of converting laterites to battery-grade nickel may lead to a shortage in the future. In Indonesia, which has been incentivizing growth in its nickel refining industry with raw nickel export bans, processing constitutes roughly 90% of the energy consumption of the full nickel production process (Wei et al. 2020). If refining technology advances do not lower the environmental impact of laterite nickel refining processes, then there may be increased risk associated with the development of battery-grade nickel supply by 2040, resulting in undersupply. In this scenario, we assume that demand for nickel in 2040 is 3000 kt, but there is undersupply with only 2200 kt of nickel sulfate supply available (as projected by Fraser et al. 2021). In response to this undersupply, prices increase in this scenario to reduce the demand such that the market is in equilibrium.

PRC EXPORT RESTRICTION ON REFINED LITHIUM CAUSES 15% REDUCTION IN GLOBAL SUPPLY

China has made a long-term and strategic shift toward leading in lithium refining, controlling more than 50% of the world's refined lithium supply (IEA 2022). The United States was a leader in lithium refining in the 1990s, but lost critical years for domestic expansion in 2018–21. It is now trying to bring more lithium refining online but will not be able to meet domestic demands in the short and medium term. In this scenario, which echoes the 2012–15 rare earth mineral trade dispute, refined lithium from China is subject to a 30% reduction in export quotas, which would result in a 15% reduction in supply for the rest of the world.

NATURAL DISASTERS IN DRC CAUSE 25% (65 KT) REDUCTION IN GLOBAL RAW COBALT SUPPLY

In 1990–94 the world's largest underground mine, the Kamoto mine, collapsed and the world's largest open pit cobalt mine flooded, both of them in the Democratic Republic of the Congo (DRC). The disasters were due to underinvestment in mining infrastructure. Other DRC mines during this period were inoperable because of worker strikes due to economic instability, so the country went from producing over 60% of the world's cobalt to less than 10% (Gulley 2022). As a result cobalt prices jumped from $17/kg to over $40/kg (Gulley 2022). The DRC now supplies more than 70% (120 kt) of the global 170 kt cobalt supply (USGS 2022). If similar disasters occur and the top three cobalt-producing mines in the DRC become inoperable, then 65 kt of cobalt would not be available globally, according to S&P mine data, causing a more than 20% reduction from the estimated 300 kt of supply in 2030.

HUMAN RIGHTS ABUSES IN ARTISANAL MINES CAUSE 14% RAW COBALT SUPPLY REDUCTION

The DRC produces 71% of global cobalt supply, 20% of which is produced in informal and unregulated (artisanal) mines (Banza Lubaba Nkulu et al. 2018), which present human rights abuse risks, particularly for women and children. The United States prevents imports of solar panels from China's Xinjiang region because of suspected human rights abuses in their manufacture (Groom 2022). A similar restriction on imports of artisanal mined cobalt would result in a 14% supply reduction for the United States.

US LITHIUM MINE DELAY CAUSES 9% (250 KT) RAW LITHIUM SUPPLY SHORTAGE

The United States is starting the process to open domestic mines, but the permitting process can be lengthy. It is expected that 250 kt of global lithium supply will be sourced from US mines in 2030, in comparison to 2.7 Mt globally in 2030, according to S&P data. If this supply does not come online by then, there will be a 250 kt global shortage of raw lithium supply, although this shortage may be mitigated by supplies from other countries, like Australia or Chile.

PRC EXPORT RESTRICTIONS SIGNIFICANTLY REDUCE NATURAL GRAPHITE SUPPLY

Graphite used in battery anodes may be natural or synthetic. Internationally produced anodes contain more natural graphite, whereas US-produced anodes contain roughly 70% synthetic graphite, whose price has historically been double the price of natural graphite (Wessel and Greenberg 2016). China controls 80% of global natural graphite mining (IEA 2022). The United States produces synthetic graphite but relies on imported natural graphite from China. In this scenario, China's natural graphite is subject to a 30% reduction in export quotas. This scenario mimics the rare earth mineral trade dispute of 2012–15, when China leveraged its market power over rare earth mineral supply to drive up global prices. If China repeated this behavior with natural graphite, the United States could substitute synthetic graphite—and anode material costs would double.

IMPACTS ON THE AUTOMOTIVE MARKET, CONSUMERS, AND MANUFACTURING WORKERS

In our baseline scenario, approximately 50% of new car purchases and 30% of new SUV purchases in the United States are BEVs. This is a projection of BEV availability in 2030 with no battery material supply chain shocks or delays (details are provided in the supporting information). The baseline BEV shares are the result of the equilibrium model simulation using projected battery pack manufacturing costs, vehicle characteristics, and estimated consumer preferences (for details, see the supporting information). The simulated shares are in line with BEV market projections from the BNEF Electric Vehicle Outlook 2023. Out of the set of identified scenarios for 2030, we model (in the following sections) three scenarios that are expected to have the largest effects on vehicle prices, consumers, and manufacturing workers based on the estimated effects on mineral prices discussed above.

PRC Lithium Export Restriction Causes 15% Reduction in Refined Lithium Supply Globally

Under this scenario, the per kilowatt-hour cost of battery manufacturing increases by approximately 25%, driving up the price of BEVs and increasing consumer demand for ICE vehicles. As a result, in the short-run (1- to 2-year) market equilibrium, the average price of both BEVs and ICE vehicles increases by $1,620 ($1,140–$2,100) for cars and

$2,120 ($1,500–$2,730) for SUVs.[1] Calculations of consumer surplus show that, on average, every car buyer is worse off by $348 ($250–$440) and every SUV buyer is worse off by $720 ($520–$920). These figures imply an annual total loss across all consumers of $24 billion ($17.3–$30.5) while vehicle manufacturer operating profits decrease or increase by less than 2%.

In this scenario, 500,000–900,000 US households are unable to purchase a new vehicle for each year that the price hike continues. This represents a contraction of new vehicle sales in the United States of 5.3% (3.8–6.8%), including a drop in BEV sales of 14% (10.0–17.9%). This drop in production could cause 29,300 (20,900–37,400) labor-months of lost wages for battery cell and pack production-line workers alone.

As shown in **figure 4-12**, the estimated impact of this scenario on the US automotive market is similar in magnitude to that of the semiconductor shortage that began in 2021. The price increase and drop in production of new vehicles that occurred with the semiconductor shortage also created large increases in used vehicle prices that persisted for more than a year.

Natural Disasters in DRC Cause 25% (65 kt) Global Raw Cobalt Supply Reduction

If natural disasters reduce DRC cobalt production by 65 kt, the average price of US new cars will increase by $1,535 ($1,083–$1,985) and SUVs by $2,145 ($1,519–$2,764), battery workers will lose 29,000 (20,700–37,000) months of wages, every car buyer will be worse off by $335 ($240–$430), and every SUV buyer will be worse off by $720 ($520–$920).

Lithium Delay Causes 250 kt Raw Lithium Supply Shortage

This scenario has a smaller impact on the automotive market. Production costs for 300-mile battery packs increase by $740 and the average new car price increases by $530. Over 100,000 US households are unable to purchase a new vehicle for each year the price hike persists.

IMPACTS OF OTHER IDENTIFIED SCENARIOS

As the results show, scenarios where the global price of refined lithium is significantly increased because of trade (or other political) disputes or the DRC supply of cobalt is significantly reduced have substantial impacts on automotive manufacturing and the average price of new vehicles, comparable to those of the semiconductor shortage that began in 2021. We anticipate that the scenarios affecting battery-grade nickel supply by 2040 would cause comparable or larger estimated increases in new vehicle prices and automotive production, considering their high impact on battery pack production costs. In contrast, the delay of US lithium mine openings and trade or political disputes affecting natural graphite have smaller impacts.

POTENTIAL MEASURES TO MITIGATE IMPACTS

The estimated impacts of future supply chain shocks and delays could be mitigated by shifting battery production toward cobalt-free chemistries, investing in less energy-intensive nickel refining, and reducing the market power of concentrated material supply at risk of trade or other political disputes.

Shift Batteries to Cobalt-Free Chemistries and Increase Energy Density of All Chemistries

Shifting US BEV production to cobalt-free battery (e.g., LFP and next-generation) chemistries would mitigate the vulnerability of US new vehicle prices and automotive manufacturing to cobalt price hikes. This shift has already partially begun, with many automakers using LFP batteries in their entry-level BEVs. LFP is typically less expensive thanks to lower costs in battery manufacturing and less price volatility in its critical minerals (IEA 2023). However, because LFP has lower energy density, some automakers prefer to use

[1] The lower and upper bounds represent the effects of the 95% confidence interval of material prices that result from the scenario. Details of these calculations are provided in the Critical Minerals demonstration summary (nncta.org).

cobalt-containing batteries in their longer-range BEVs. Developing LFP and next-generation chemistries to increase performance at the battery pack level could reduce US reliance on cobalt.

Reduce Environmental Impacts and Costs of Nickel Refining

Investing in supply-side technologies that can refine nickel laterite to battery grades at lower costs and with better environmental impacts than current processing technologies can provide battery manufacturers with the necessary nickel supply. Reducing reliance on coal-based energy for refining and improving tailings management can help mitigate environmental impacts of laterite refining, but can add to already high costs. Technological improvements that reduce refining costs will be key to ensuring that laterites can be used as a sustainable long-term source of battery-grade nickel.

Reduce Market Power of Concentrated Material Supply at Risk of Trade or Other Political Disputes

As the results show, large price increases in batteries are possible because of the geographic concentration of refined lithium in China, and similarly large price increases may result if cobalt supply is restricted because of natural disasters or a leveraging of market power and if BEV batteries do not shift to cobalt-free chemistries. Diversification of supply sources for these materials can enhance resilience to disruptions and mitigate impacts on new vehicle prices, US consumers, and manufacturing workers. The Inflation Reduction Act and subsequent guidance proposed by the IRS and Treasury Department[2] are expected to incentivize supply chains in this direction by limiting BEV tax credits for vehicles with batteries containing critical minerals extracted or processed by a non–free trade agreement country. R&D efforts that improve supply-side technologies, such as direct lithium extraction, may also expand domestic supply.

[2] Section 30D New Clean Vehicle Credit, https://www.federalregister.gov/documents/2023/04/17/2023-06822/section-30d-new-clean-vehicle-credit

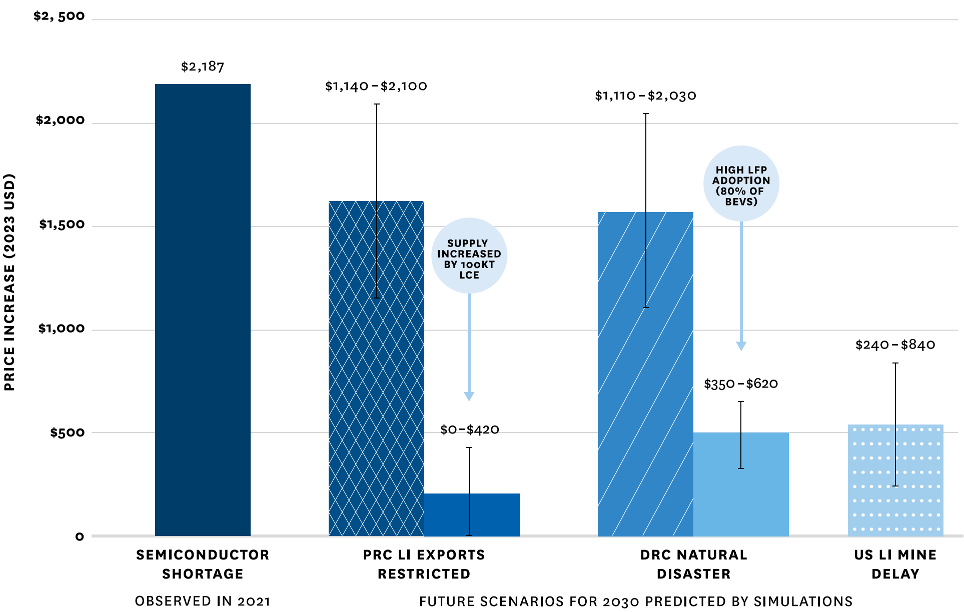

FIGURE 4-12. Average US new car price increases in future scenarios compared with those associated with the semiconductor shortage that began in 2021. BEV = battery electric vehicle; DRC = Democratic Republic of the Congo; LCE = lithium carbonate equivalent; LFP = lithium-iron-phosphate; Li = lithium; PRC = People's Republic of China

Continue Investment in Best Technologies and Practices for Extraction and Recovery

Continued access to secondary supply through recovery and recycling would also mitigate the impact of primary supply restriction. Under ideal conditions, retired batteries could supply more than half of global demand for cobalt, lithium, and nickel in 2040 (Dunn et al. 2021). However, with dramatically increasing demand for EVs, secondary supply from end-of-life batteries is not expected to be a significant source of supply before 2040. Industry learning and domestic capability development to manage and process manufacturing scrap could provide another source of recycled supply. Support of existing and emergent domestic resources and circular pathways for materials through programs such as NSF TIP's Regional Innovations Engines and ARPA-E's MINER, hold the potential to improve these capabilities and increase supply resilience in the future.

When considering incentives to expand production domestically and in other countries, it is essential to consider impacts on the communities surrounding mining and refining sites. For example, 90% of graphite, 87% of lithium, 76% of nickel, and 72% of cobalt resources globally are located on or near Indigenous and peasant lands (Owen et al. 2022). To foster an equitable energy transition, the United States should encourage engagement of affected communities before, during, and after the permitting process to ensure that they receive benefits from mining and manufacturing developments. Local community and environmental impacts of extraction and processing are not included in the current modeling approach; future work could incorporate metrics of these impacts.

Vision for Future Analytical Work

In analyzing scenarios of battery material supply shocks and delays, this project sought to identify the sources of vulnerability in BEV battery material supply chains and impacts on the US automotive market, consumers, and manufacturing workers. Future work will examine the influence of potential actions that would buffer the impacts of the identified scenarios, including existing measures (e.g., through the Inflation Reduction Act) as well as potential government and industry investments to increase supply chain resilience (e.g., to expand domestic extraction and processing or strategic reserves of materials). The model could be enhanced by incorporating possible industry shifts in anticipation of the material supply shocks or delays, such as novel mineral extraction and processing technologies, integrated recovery architectures, and the battery materials and automotive industries' responses to anticipated future materials prices, such as changes in the mix of battery chemistries and improvements in vehicle energy efficiency to reduce material requirements. Future analysis will evaluate technological developments and investments that would help to achieve these resilience measures.

Some gaps in data could be addressed by future research and modeling. Our model represents a global market for battery materials, but vertical integration and independent contracts between battery manufacturers and miners affect supply chain vulnerabilities. Research is needed to understand the impacts of vertical integration and long-term contracts on the battery material markets. There are also nuances in the natural and synthetic graphite markets; detailed graphite supply data would help to further develop the model to accommodate these separate markets.

Finally, preliminary research suggests that LFP is more robust to high-speed charging than some other chemistries currently used in EVs. This early finding, if true, has equity implications for low-income vehicle owners who tend to buy second-hand vehicles and are more likely to lack home charging and thus be more dependent on high-speed public charging infrastructure.