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HOW TECHNOLOGY, RECYCLING, AND POLICY CAN MITIGATE SUPPLY RISKS TO THE LONG-TERM TRANSITION TO ZERO-EMISSION VEHICLES

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EXECUTIVE SUMMARY

To address the urgent need for clean air and a stable climate, governments around the world are increasingly acting to transition their transport sector entirely to all zero-emission vehicles (ZEVs). A ZEV transition requires ramping up global ZEV production from 2 million vehicles in 2019 to tens of millions by 2030, and eventually to all ZEVs to meet future demand and climate goals. Such a dramatic shift to ZEVs prompts questions about potential supply constraints that could slow the transition, including questions about the supply chain for batteries and about the electric vehicle production facilities needed to meet ZEV targets across China, Europe, and North America.

This report analyzes fundamental ZEV supply questions from raw materials, through battery and vehicle production, to consumer supply of ZEVs. The analysis quantifies the amount of materials such as lithium, nickel, cobalt, and graphite that are needed in the electric transition, incorporating improved battery chemistry over time. Although the analysis is focused primarily on passenger vehicles, additional analysis incorporates the broader context of battery demand from other transport applications and other sectors. The findings are compared against estimates for proven raw material reserves, and the effect of large-scale battery recycling is analyzed. Ultimately, we draw conclusions to provide governments with an improved understanding of the associated supply dynamics and actions that could mitigate any associated risks.

From this analysis, we draw the following five conclusions related to how technology, recycling, and policy can mitigate supply risks to the long-term transition to ZEVs.

Continued global efforts are needed to ensure that electric vehicle, battery, and material supply demands are met. This analysis indicates that electric vehicle and battery production can meet needs for government requirements and targets through 2025. Although battery production is tight in 2021–2022, the expanded battery cell and pack production already under development is well above the required near-term ZEV deployment from regulations around the world. What is less clear is whether the pace and scale of upstream raw material mining and refining into battery-grade quality is sufficient to keep pace with battery cell, pack, and vehicle manufacturing. The rush of capital into electric vehicles includes auto industry investments adding up to $180 billion in vehicle manufacturing, plus battery procurement investment of another $500 billion. This capital will need to flow upstream to unlock more mining and spur expanded refining capacity so that battery-grade materials are available to feed into battery cell production across Asia, Europe, and North America.

Raw material reserves are more than sufficient to support the global transition to ZEVs. Raw material needs for batteries for a transition to ZEVs will increase the annual need for cobalt, manganese, lithium, nickel, and graphite by 5 to 23 times from 2020 to 2035. Industry innovation and commercial developments toward increased battery specific energy and greatly reduced amounts of key materials (most prominently, at least 75% less cobalt per battery pack kilowatt-hour), will significantly reduce global material supply issues, even as ZEV deployment increases. Battery material needs for global passenger electric vehicles by 2035 reach 8% to 14% of proven global reserves for lithium, nickel, and cobalt. After accounting for battery demands for other sectors, battery material demand is approximately doubled.

A significant potential ZEV supply constraint is the supply of electric vehicle models to consumers. Despite the less-certain upstream developments to increase material mining and refining capability, the announced increase in electric vehicle and battery pack production volumes exceed annual global demand of 20 million electric vehicles sold and 1,100 gigawatt-hours of batteries supplied by 2025. This is more than sufficient to cover the world's regulatory requirements in China, Europe, and North America that have been adopted through 2020. However, because some states and countries have more aggressive 100% ZEV targets and are supporting those with higher levels of incentives, infrastructure, and consumer programs, there will be constraints from market to market (e.g., California in the United States, Québec and British Columbia in Canada, Norway and the United Kingdom in Europe).

Battery recycling practices will have a profound effect on long-term ZEV battery material supply. The analysis indicates that developing recycling streams to recover approximately 90% of the critical battery materials can significantly reduce the need for raw material mining from 2040 on. When accounting for second-life use of batteries after electric vehicle end-of-life, recycling can reduce the need for new material mining by 20% in 2040 and 40% in 2050. With recycling, the cumulative use of lithium and nickel could reach 25% of known global reserves by 2050, and 30% for cobalt. This is approximately a 25% reduction in the cumulative use of materials as a percentage of known global reserves in 2050 compared to a no-recycling case. Without recycling, cumulative use of these three key materials for global passenger electric vehicles could reach 30% to 40% of global proven reserves by 2050. Beyond 2050, as greater volumes of batteries become available for recycling, the need for new mining can be further reduced.

Comprehensive industrial-to-consumer policies are key to minimizing ZEV supply chain bottlenecks. Industry incentives, including for battery upstream raw material supply chain development, ensure key components reach higher volumes more quickly. Vehicle-level regulations for 2030–2040 requiring higher levels of electric vehicle production with sufficient lead time create certainty for industry investments and drive volume for more models to reach more markets. Demand-side support, such as incentives and infrastructure, provide near-term consumer support as technologies reach greater scale. Continued tracking of these supply chain steps is key to assessing where issues could emerge. Government actions can help bolster the financial viability of raw material extraction and refining to ensure battery-grade materials are sufficient to feed the projected demand. Cross-industry collaboration, public-private partnerships, transparency and traceability, and recycling regulatory and incentive measures are warranted to ensure batteries are designed for recyclability, collected upon end-of-use, and ultimately recycled. Government regulations for battery recycling would optimally focus primarily on the materials with the highest value and the greatest supply risk.

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INTRODUCTION

To address clean air and a stable climate, governments around the world are increasingly acting to transition their transportation sectors entirely to all zero-emission vehicles (ZEVs). Transitioning to ZEVs is a key pillar in the global efforts to mitigate climate change, and the benefits of doing so increase dramatically over time to more than 1.5 billion tons of CO_2 per year in 2050 (Lutsey, 2015). Beyond the emission-reduction and energy security benefits, governments look to capitalize on the broader economic benefits from industrial transition to ZEVs, including automotive and infrastructure employment and the consumer fuel-saving benefits. Such a transition requires ramping up global ZEV production of 2 million vehicles a year in 2019 to tens of millions by 2030, and eventually to all ZEVs to meet future demand and climate goals.

Prevailing barriers exist that hinder the widespread global adoption of ZEVs, including cost, infrastructure, awareness, and model availability. That last barrier – model availability – is critical, as increased availability of electric vehicle models in higher volumes and across more vehicle segments is a key precursor to the transition to all ZEVs. A dramatic shift to ZEVs prompts questions about potential supply constraints that could slow the transition. Initially there are supply chain questions about whether the critical high-quality battery-grade materials like nickel, lithium, and cobalt are being produced quickly enough, followed by whether battery cell production facilities are being built quickly enough for automakers. Beyond these material and cell-level concerns are questions about whether sufficient battery pack and electric vehicle production facilities are in the works to meet vehicle regulation requirements through 2030 in China, Europe, and North America, and the proliferating 100% ZEV targets by governments (Lutsey, 2018a; Cui, Hall, & Lutsey, 2020). Even with ZEV cost parity and government funding for incentives and infrastructure, the barrier of consumer model availability across given markets may yet remain (Slowik, Hall, Lutsey, Nicholas, & Wappelhorst, 2019; Transport & Environment, 2019a).

This report analyzes fundamental ZEV supply questions from the consumer supply of ZEVs to vehicle and battery production and raw materials. It evaluates how the announced future electric vehicle production and consumer supply compares to government near-term regulations and long-term targets, and how future battery manufacturing capacity compares to global demand. The analysis quantifies the amount of materials like lithium, nickel, cobalt, and graphite needed in the transition to electric vehicles, incorporating improved battery chemistry over time. The findings are compared against estimates for proven raw material reserves, and the effect of large-scale battery recycling is analyzed. The report does not comprehensively assess how the material refining and chemical processing capacity compare with battery-grade material demand. Although the analysis is primarily focused on passenger electric vehicles, additional analysis incorporates the broader context of battery demand from other transport applications and other sectors. Ultimately, we draw conclusions to provide governments with an improved understanding of the associated supply dynamics and actions that could mitigate any associated risks.

BACKGROUND

As context for this paper's analysis of understanding ZEV supply dynamics, this section provides background in several areas. A brief review of global ZEV trends and the key supply challenges going forward is provided to frame the potential issues surrounding the global transition to ZEVs. The key components of the ZEV supply chain are described to provide context for the following sections of this assessment of understanding ZEV supply dynamics.

ZEV SALES TRENDS AND DISTRIBUTIONS

Global ZEV market growth continues, with the world's stock of electric passenger vehicles surpassing 7 million in 2019. Figure 1 illustrates the global growth in electric vehicle sales from 2010 through 2019. As shown, annual electric vehicle sales have increased from a few thousand in 2010 to more than 2.2 million in 2019, representing about 2.5% of all new vehicles sold worldwide in 2019. The figure shows the relative sales in the major regions, where the major electric vehicle markets in North America are shown in blue, those in Europe are shown in green, and those in Asia are shown in red. Together, the 11 markets identified account for about 92% of ZEV sales through 2019.

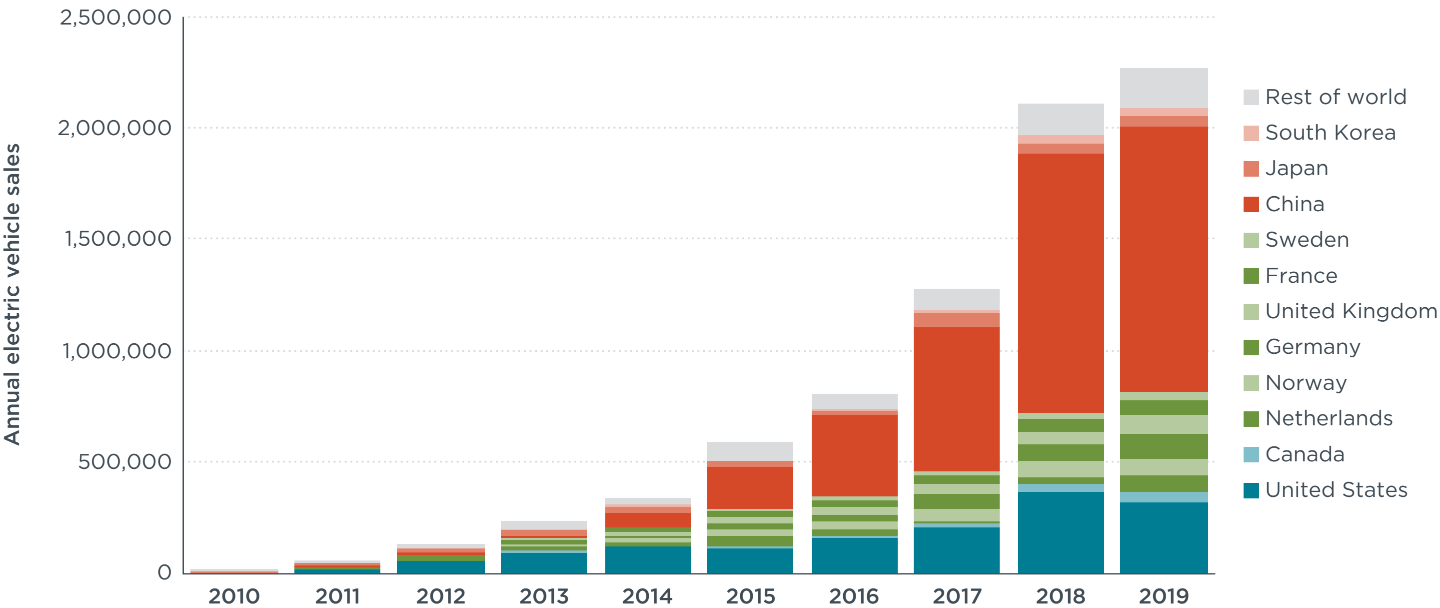

Figure 1. Global electric vehicle sales from 2010 through 2019 (based on EV-Volumes, 2020).

Sales trends and the global distribution of ZEVs have important implications for understanding ZEV supply dynamics because most electric vehicles are manufactured in the same region in which they were sold (Lutsey, Grant, Wappelhorst, & Zhou, 2018). Figure 2 illustrates the broader dynamics of the global electric vehicle industrial developments from 2010 through 2019, including the electric vehicle sales, electric vehicle production, and electric vehicle battery production in China, Europe, the United States, Japan, South Korea, and Canada. The electric vehicle sales and production, and the estimated battery pack production, are based on electric vehicle model sales data from EV-Volumes (2020), as well as industry reports. Together, these six regions account for approximately 98% of global electric vehicle sales, electric vehicle production, and battery production. The same bars can also be read as a percentage of the cumulative global electric vehicles (about 7.8 million through 2019) on the right axis. Through 2019 about 80% of electric vehicles sold were manufactured in the same region in which they were sold.

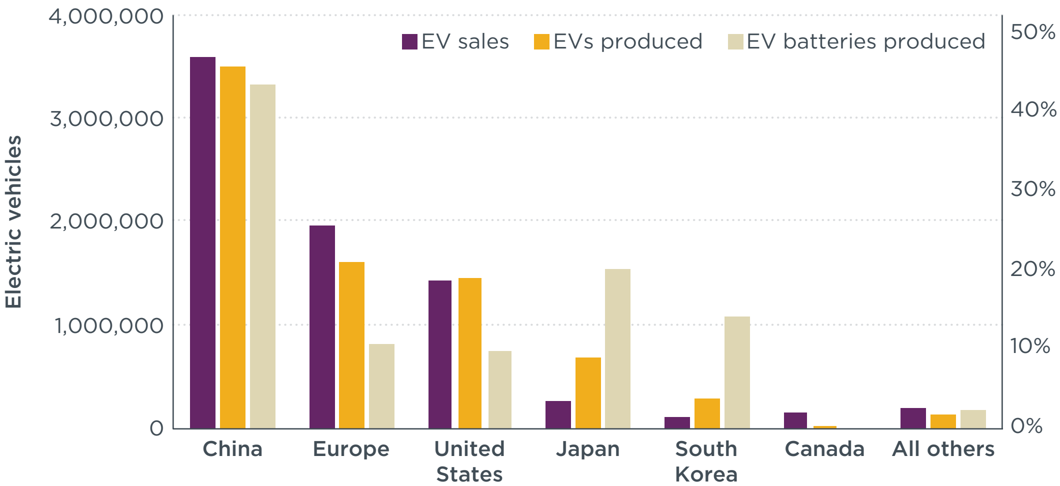

Figure 2. Electric vehicle sales, electric vehicles produced, and electric vehicle battery production by region through 2019, with percentage of global electric vehicles on right axis (based on EV-Volumes, 2020).

Figure 2 shows how some of the major regions, such as Europe and Canada, are net electric vehicle importers (i.e., production is less than sales) whereas others including Japan and South Korea are net exporters. Similarly, some regions are battery importers and others are exporters. Relative to vehicle sales and production, Japan and South Korea stand out as having produced many more battery cells than vehicles, whereas battery production in Europe and the United States is about half that of the number of electric vehicles produced. Electric vehicle and battery manufacturing in Canada through 2019 appears to be relatively limited. Data for China, on the left of the figure, show that it is the largest electric vehicle market in terms of vehicle sales and production, as well as batteries produced and accounts for about 45% of each of these globally. China has had comparatively little import and export of electric vehicles or batteries. These dynamics can be seen by where individual electric models are made and predominantly sold. In global terms, 17 of the top 20 highest-selling global electric vehicle models are manufactured in their highest-selling regional markets (e.g., BAIC and BYD models in China, BMW and Renault models in Europe, Tesla models in the United States).

Electric vehicle sales and production as well as battery production are driven by a mix of industrial and consumer promotion policies. Figure 2 summarizes the high-level snapshot of the broader industry developments globally, but deeper insight into the industry decisions at the regional or local level with regard to the supply and availability of electric vehicles and their batteries is needed to more comprehensively understand ZEV supply dynamics and the policy opportunities to bolster it. We explore this in greater detail in the analysis that follows.

OVERVIEW OF KEY ZEV SUPPLY CHALLENGES

Availability and supply of electric vehicle models in sufficient volume across the major vehicle segments is a limiting factor to greater ZEV adoption in many markets. Furthermore, there is evidence that ZEVs are preferentially supplied to those regions with the strongest mix of supporting policies. In particular, ZEV regulations and emission standards encourage automakers and their suppliers to bring advanced technology vehicles to market and help to overcome this barrier by increasing ZEV supply (Slowik & Lutsey, 2018; Rokadiya & Yang, 2019).

The electric vehicle supply chain is complex and multifaceted; several critical upstream processes occur before the final point at which consumers possess electric vehicles. Broadly speaking, we assess four key challenges to the electric vehicle supply chain: resources, manufacturing, regional distribution, and consumer demand. Resources include the critical battery raw materials like lithium, cobalt, nickel, and graphite; the known global reserves of these materials; and the extraction and refining facilities for producing them. Manufacturing includes the production and assembly of ZEVs and their batteries and growth in production facilities to manufacture ZEVs. Regional distribution includes industry decisions about which local or regional markets to supply electric vehicle models to and includes key considerations like the volume and vehicle segments of electric model that are available, manufacturing vehicles with left- or right-hand drive, homologation, and safety standards. Consumer demand challenges include electric vehicle inventory bottlenecks, availability at local dealerships, and consumer wait times to purchase new models in different jurisdictions.

The analysis of ZEV materials is focused on passenger electric vehicle batteries, which require high volumes of several critical materials that have historically had relatively low-volume global material flows to vehicles. High-volume commodity materials that are used in all vehicles including copper, steel, iron, and others are excluded from this analysis, because they have much higher flows through the automotive industry already, although we note that specific processes are needed to refine these materials into battery-grade quality. Precious metals, rare earth elements, magnets, high purity alumina, and other low-volume specialized components used in electric motors are not included in the analysis. Although the literature indicates potential supply issues with rare earth elements (Ballinger et al., 2019), they are components of multiple motor types, are also in hybrid motors, and the global demand for some of them is greater from the renewable electricity sector than ZEVs (Bosch, van Exter, Sprecher, de Vries, & Bonenkamp, 2019).

This analysis is primarily focused on the core materials associated with the evolution from the internal combustion engine to a 250- to 500-kilogram lithium-ion battery pack. It does not include materials used in charging infrastructure, which contain very small quantities of critical metals compared to vehicle batteries (Bosch et al., 2019). Although this analysis focuses on electrification, deployment of fuel cell vehicles is less dependent on the materials assessed. Greater deployment of fuel cell vehicles, which do not have battery packs and the associated lithium, cobalt, nickel, and graphite, would further reduce potential vehicle, battery, and raw material related supply challenges from what is reported here. At the same time, parallel developments to supply fuel cell vehicles with renewable electricity could further increase resource needs in the energy sector.

To provide context to the ZEV share of the global lithium-ion battery landscape, transportation electrification represented approximately half of global lithium-ion battery demand in 2018, up from about one-third in 2015. Other applications and products like consumer electronics and stationary storage require lithium-ion batteries. Consumer electronics including cell phones, laptops, tablets, cameras, and power tools have historically dominated global lithium-ion battery demand, and in 2018 consumer electronics represented about 40% of the lithium-ion battery market whereas stationary energy storage represented less than 10%. As the world shifts to ZEVs, transportation will represent an increasingly larger share of lithium-ion battery demand. The growth rate and associated lithium-ion demand of consumer electronics and stationary storage is projected to be significantly lower than that of ZEVs (Ding, Cano, Yu, Lu, & Chen, 2019; Melin, n.d.; Bloomberg New Energy Finance [BNEF], 2019; Interact Analysis, 2019; Avicenne Energy, 2017a). The analysis below on ZEV battery supply puts this analysis in that broader context.

This analysis focuses primarily on four critical materials—lithium, cobalt, nickel, and graphite. These materials are those most commonly cited in the literature, strategic government documents, and industry commentary for their potential risks. The International Energy Agency Taskforce 40 (2020) and European Commission (2019) list lithium, cobalt, nickel, and graphite as a critical raw material for batteries. Cobalt and lithium are labeled by governments as “strategic” for their importance to emerging technologies, and “critical” based on their risk of supply disruption (Leon & Miller, 2020). The Nordic Council of Ministers finds the highest associated supply risk is associated with lithium and cobalt (Dahllöf, Romare, & Wu, 2019). Investment group and media reports identify lithium, cobalt, and nickel as top risks for supply barriers (Behr, 2020; Stringer, 2019; Stringer & Ritchie, 2018; Massif Capital, 2019). A 2018 U.S. International Trade Commission article lists lithium, graphite, and cobalt as the materials that could face supply constraints (Coffin & Horowitz, 2018).

Like the extraction of any other natural resource, mining of raw materials for electric vehicle battery packs faces further upstream supply concerns. Key challenges include the pace and scale of mining, the geographic concentration of raw materials, and potential market price volatility. Other key upstream challenges include local environmental impacts, greenhouse gas emissions, social issues that affect the communities associated with mining operations, and general lack of traceability and transparency in the raw material supply chain (International Energy Agency, 2019).

In this paper, we systematically analyze the potential for future global ZEV supply limitations as follows. The following third section assesses key global ZEV developments, including announcements, investments, business decisions, and goals in the private and public sectors. The fourth section analyzes the potential to achieve increasing ZEV demand and the potential supply-side issues in raw materials including lithium, cobalt, and nickel for batteries, and growth in vehicle and battery production facilities to manufacture ZEVs for the growing market. The fifth section discusses how policies, including regulatory, industrial, and consumer-focused programs, are affecting industry decisions and the opportunities for policy to reduce the associated ZEV supply barriers. Finally, conclusions are drawn from the analysis.

ASSESSMENT OF ZEV DEVELOPMENTS

This section analyzes global electric vehicle and battery developments. It assesses electric vehicle and battery pack sales through 2019, as well as future annual electric vehicle sales and battery production in the major global markets based on industry announcements and government near-term regulations and long-term targets.

INDUSTRY ELECTRIC VEHICLE AND BATTERY DEVELOPMENTS

Analyzing global electric vehicle sales by manufacturing company and the associated battery suppliers provides more granularity into the emerging industry, including the number and relative production volumes of the major companies through 2019. Figure 3 shows the annual sales of electric vehicles and the associated battery pack sales by company. Vehicle manufacturers are shown on the left and battery supplier companies are on the right. The figure is based on electric vehicle sales data from EV-Volumes (2020), as well as industry reports. As shown, the number of companies manufacturing electric vehicles and their batteries has greatly increased with the volume of vehicles and batteries manufactured.

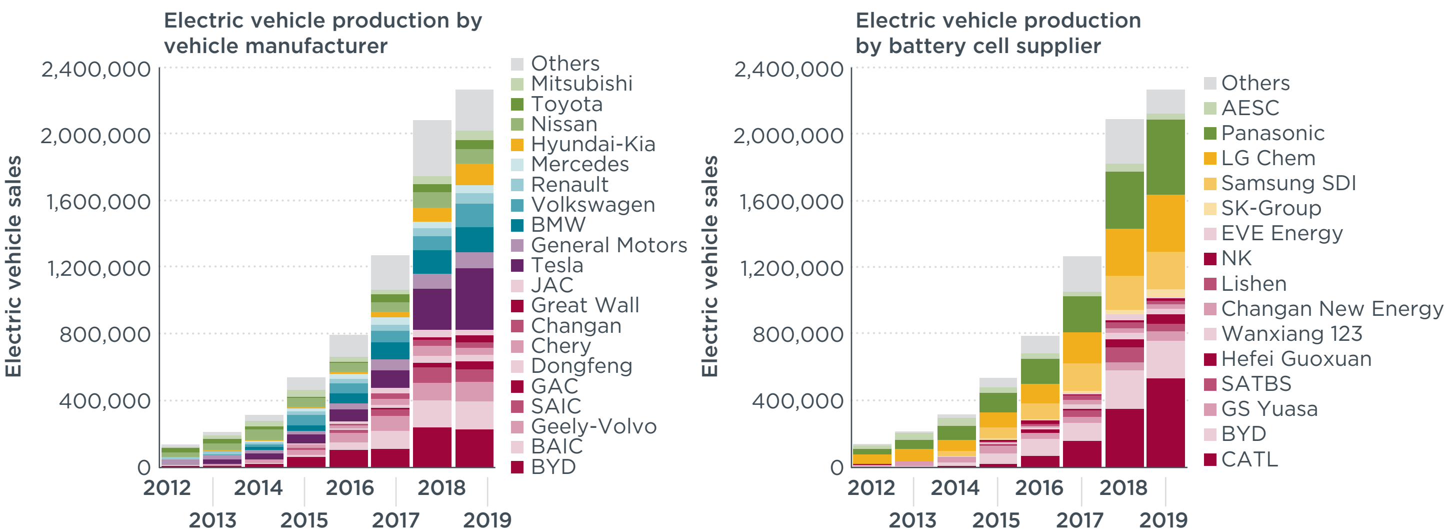

Figure 3. Electric vehicle and battery pack cell production by automobile manufacturer and battery pack supplier for 2010–2019 (based on EV-Volumes, 2020).

The companies in Figure 3 are listed based on the region in which they are headquartered, which is shown by the clusters of companies in each general color category. For example, shades of red are for China, purple are for the United States, blue are for Europe, orange are for South Korea, and green are for Japan. In terms of vehicle manufacturing, there were 20 companies that manufactured at least 30,000 electric vehicles in 2019, and 10 companies (BAIC, BMW, BYD, Geely-Volvo, General Motors, Hyundai-Kia, Nissan, SAIC, Tesla, Volkswagen) manufactured more than 75,000. Precise categorization of vehicles by company and headquarters region is more complex than shown due to joint ventures, alliances, and combined efforts among suppliers and automakers on vehicle components.

In terms of battery production, there are fewer battery companies than vehicle manufacturing companies, indicating how battery suppliers serve multiple vehicle manufacturers and are achieving higher production volume each year. We estimate that there are five battery companies (CATL, Panasonic, LG Chem, Samsung, and BYD) that produced cells for more than 200,000 electric vehicle battery packs in 2019, with CATL producing batteries for more than 500,000 electric vehicles. Of the 15 battery companies shown, 10 are headquartered in China, two in Japan, and three in South Korea. Although the figure shows the regions in which the companies are headquartered, these companies are largely global, have joint ventures, and often have battery production facilities in several regions (e.g., LG Chem in Poland, Panasonic in the United States).

Global growth of electric vehicle manufacturing is expected to continue; most major automobile manufacturing companies are investing billions of dollars to develop new models and greatly increase manufacturing volumes. Table 1 summarizes the announcements of more than 20 manufacturers, including the amount of investment, number of electric model offerings, and the electric vehicle sales (and sales shares). The largest public announcement is a $100 billion investment from the Volkswagen Group, which includes $40 billion in electric vehicle manufacturing and $60 billion in battery procurement for Volkswagen, Audi, and other affiliated brands. The group has announced offerings of 70 new electric models by 2028, an electric variant on all 300 of its models by 2030, and its aim to sell 4–5 million vehicles annually by 2030 (approximately 40% of sales).

Table 1. Automaker electric vehicle model offerings and sales targets.

Automaker group	Announced investment	Electric models	Annual global electric sales (share)
Volkswagen Group	• $40 billion manufacturing plant by 2022 • $60 billion battery procurement	• 70 electric models by 2028 • 300 electric models by 2030	• 4–5 million (40%) by 2030
Nissan-Renault-Mitsubishi	• $9.5 billion over 2018–2022 (China)	• 20 electric models by 2022 (China)	• 3 million (30%) by 2022
Toyota-Suzuki-Mazda-Subaru	• $2 billion over 2019–2023 in Indonesia	• All vehicles hybrid, battery, or fuel cell electric by 2025	• 2–3 million (15%) by 2025
Honda	• $430 million facility in China • $300 million for battery plants	• 100% hybrid or electric sales in Europe by 2025 • 20 electric models in China by 2025	• 2 million (30%) by 2030
Chongqing Changan	• $15 billion by 2025	• 21 electric models by 2025 • 12 plug-in hybrid models by 2025	• 1.7 million (100%) by 2025
Mercedes	• $13 billion manufacturing plant • $1.2 billion battery manufacturing • $22 billion battery procurement	• 10 electric models by 2022 • 50 electrified models by 2025	• 1.5 million (50%) by 2030
BAIC	• $1.5 billion by 2022 • $1.9 billion (with Daimler)	• (not available)	• 1.3 million (100%) by 2025
Geely	• $3.3 billion	• Al models hybrid or electric by 2019 (Volvo)	• 1.1 million (90%) by 2020
Tesla	• $5 billion factory in Shanghai • $4.4 billion factory in Berlin	• 6 all-electric models	• 1 million (100%) by 2022
Hyundai	• $16 billion through 2025	• 23 BEV, 6 PHEV, 2 FCEV by 2025 (Hyundai Motor Group)	• 1 million (15%) by 2025

Automaker group	Announced investment	Electric models	Annual global electric sales (share)
BMW	• $11 billion battery procurement from 2020–2031	• 13 electric models by 2025 • 12 plug-in hybrid models by 2025	• 900,000 (30%) by 2030
General Motors	• $2.3 billion battery factory • $2.2 billion electric vehicle plant	• 20 electric models by 2023	• 1 million (12%) by 2026
Kia	• $25 billion through 2025	• 11 battery electric vehicles by 2025	• 500,000 (15%) by 2026
Fiat Chrysler	• $22 billion to develop hybrid and electric vehicles through 2022	• 30 nameplates will have hybrid or electric options by 2022	• 250,000 (10%) by 2025 in China, North America
Smart	• (not available)	• Only all-electric options from 2020 in Europe and the United States	• 100,000 (100%)
Ford	• $11 billion by 2022	• 16 all-electric models by 2022	• (not available)
PSA Group	• $250 million in electric motors • $90 million in transmissions	• Hybrid or electric options of all models by 2025	• (not available)
Great Wall	• $2–8 billion over 10 years	• (not available)	• (not available)
BYD	• $3 billion on battery factories by 2020 • $1.5 billion Changzhou NEV factory	• (not available)	• (not available)
Jaguar Land Rover	• $18 billion over 2019-2022	• Hybrid or electric options of all models by 2020	• (not available)
Infiniti	• (not available)	• All new models plug-in hybrid or electric by 2021	• (not available)

Based on updates from: Lutsey (2018a); Lutsey et al. (2018); Lienert & Chan (2019); estimations based on public company announcements
Note: numbers in the table are rounded

The publicly available automaker announcements shown in Table 1 represent about $275 billion in worldwide investments. For context, other reports from April 2019 estimate automaker investments amounting to $300 billion in electric and autonomous vehicle development (Lienert & Chan, 2019). Earlier analyses from May 2018 found that collective automaker electric vehicle investments summed up to $150 billion, reflecting a near-doubling of announced investments since 2018 (Lutsey et al., 2018). Similarly, the number of major automakers that have publicly announced their electrification commitments has approximately doubled since 2018. Many strategic plans are not publicly announced (e.g., BYD is among the largest electric vehicle and battery companies, but it has shared less information), so the actual investments are likely greater than shown here. Despite the global COVID-19 crisis providing an unknown and unsteady environment for near-term automobile manufacturing, the majority of automaker electric vehicle investments and targets do not appear to have been significantly delayed.

Figure 4 depicts what the automaker announcements summarized in Table 1 translate to in terms of global growth in annual electric vehicle sales. The figure shows annual electric vehicle sales by manufacturer from 2015 through 2025, including actual sales data through 2019 and estimates based on the industry announcements in Table 1 for 2020 through 2025. The companies are ordered from bottom to top based on the highest annual electric vehicle sales in 2025. As shown, the automaker targets sum up to about 20 million electric vehicles per year in 2025. These announcements reflect an approximate 50% year-over-year increase in electric vehicle sales from 2019 to 2025 and indicate that manufacturing volume will continue to ramp up significantly.

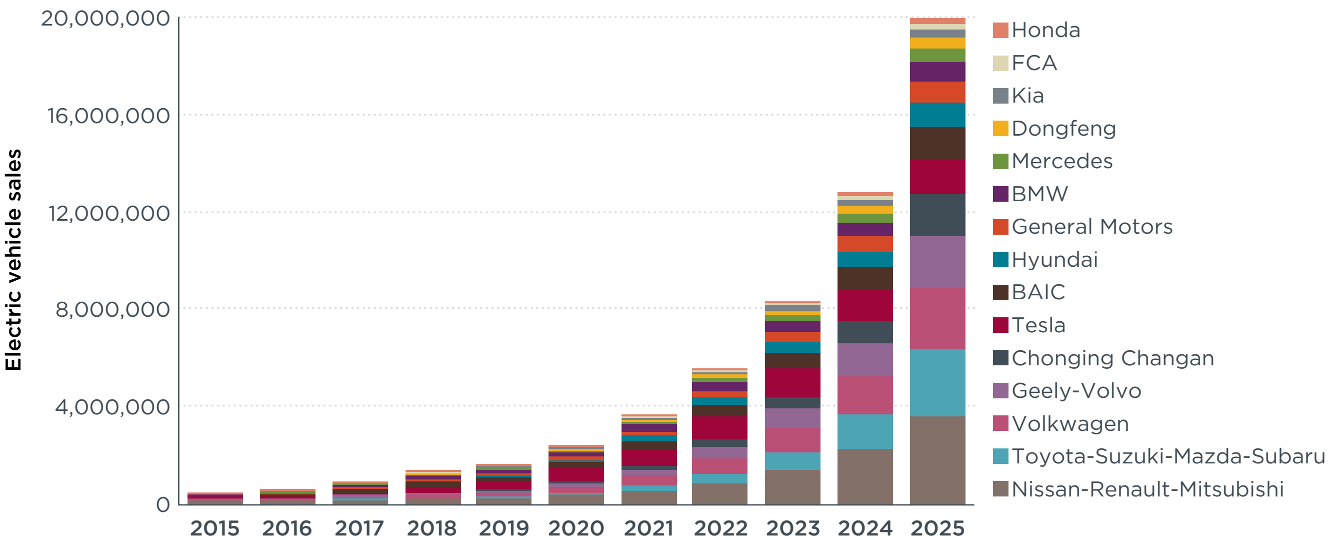

Figure 4. Annual ZEV sales through 2019, and future sales estimates based on automaker announcements.

Growth of electric vehicle manufacturing and battery production occur in unison. Like the vehicle manufacturing companies, many battery suppliers are investing billions of dollars to increase battery cell production as they develop new chemistries. Figure 5 illustrates the growth in global electric vehicle battery cell production capacity in gigawatt-hours (GWh) from 2020 through 2025, with battery production companies shown on the left and region of production shown on the right. The figure is based on many different research reports and industry announcements (Argus Media Group, 2019a; International Energy Agency, 2019; Lutsey et al., 2018; Michaelis et al., 2018; Tsiropoulos, Tarvydas, & Lebedeva, 2018; Yang & Jin, 2019). The companies shown in the left of Figure 5 are listed based on the region in which they are headquartered, which is shown by the clusters of companies in each general color category. Shades of red are for China, blue are for Europe, green are for Japan, and orange are for South Korea. One company shown is outside these regions: Energy Absolute is headquartered in Thailand. As shown, the industry announcements for new and expanded battery manufacturing facilities sum up to more than 500 GWh in new global capacity by 2022 and nearly 1,000 GWh by 2025. To provide context to the announced growth, in 2019 there was 95 GWh of actual passenger electric vehicle battery production.

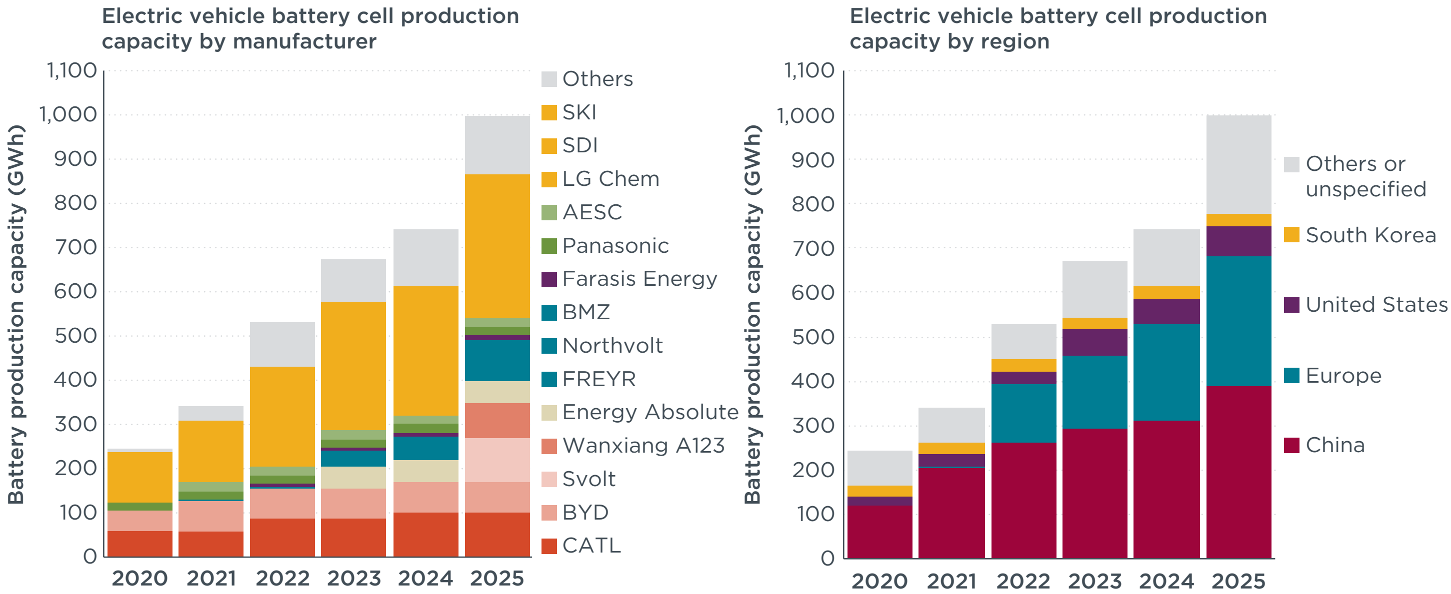

Figure 5. Announced electric vehicle battery pack production capacity for 2020 through 2025, by company and region.

Based on the industry announcements shown in Figure 5, global 2025 production capacity would be about 11 times the actual battery cells produced for passenger electric vehicles in 2019. This amounts to about a 26% year-over-year increase in production from 2020 through 2026. To provide context to the 95 GWh of actual passenger electric vehicle battery production in 2019, BNEF (2019) reports that there was about 316 GWh of commissioned lithium-ion battery production capacity in 2019. From this, it is clear that not all production facilities are operating at full capacity (especially as new plants are quickly coming on line), and there are many other applications for lithium-ion batteries beyond passenger electric vehicles, including other vehicle segments and nonautomotive applications.

Overall, Figure 5 shows the general trend for more battery manufacturing by more companies in more regions. The figure on the left shows that there are at least 10 companies that are adding 20 GWh or more in battery cell manufacturing capacity by 2026. Six companies—LG Chem, CATL, SK Innovation, SVolt, BYD, and Wanxiang Group—have announced plans to add more than 80 GWh in battery cell manufacturing capacity manufacturing capacity by 2025. These companies are expanding within and across the major regions. For example, LG Chem will operate seven total battery production facilities in South Korea, China, the United States, and Europe by 2024 (LG Chem, 2019).

The right of Figure 5 shows the breakdown of where the new battery manufacturing would occur. As shown, most of the announced growth through 2025 would occur in China and Europe, with about 400 GWh of new battery manufacturing capacity in China and more than 300 GWh in Europe. The regional location of more than 200 GWh or about 20% of the announced future battery manufacturing capacity is yet to be identified, indicating the major industrial opportunity going forward. We note that the total investments in new or expanded battery production facilities is not always disclosed, and thus the actual total investment is likely greater than this. Benchmark Mineral Intelligence, for example, estimates that there is over 2,000 GWh of capacity in the pipeline for 2028, about twice the growth shown through 2025 in Figure 5 (Benchmark Mineral Intelligence, 2019). Although the exact battery pack production through 2025 is uncertain, as some of the announcements could get delayed or cancelled, there are also likely to be other new plants or plant expansions that have not been publicly announced.

Several additional notes help give context to the investments being made to support these battery production developments. Not shown in Table 1, the announced investments by battery suppliers toward new and expanded battery manufacturing facilities from 2020 to 2025 sum up to more than $33 billion. Another indication of the momentum toward additional battery investments is apparent in the European Union Battery Alliance 2018 announcement, wherein then-European Commission vice president Maroš Šefčovič described the potential annual battery market value chain as being worth 250 billion euros to build 10 to 20 factories of at least 1 GWh in Europe (European Commission, 2018). Further analysis below provides additional context on the value of battery procurement based on projected electric vehicle deployment through 2030.

The growth of global battery manufacturing capacity shown in Figure 5 refers to announced battery cell- and pack-level production and does not include upstream investments needed to produce the battery-grade materials needed for cell manufacturing or the mines needed to extract raw materials from the ground. Investments will need to flow upstream to ensure that the pace and scale of raw material mining and chemical refining parallels that of battery and ZEV manufacturing. Industry announcements about the level of investment, anticipated timeline, and expected production volume for new and expanded mining and refining are generally less publicly available compared to industry announcements for ZEV and battery manufacturing. Developments in 2020 include European Union funding and permitting for lithium mines in Spain, Austria, and the Czech Republic (Argus Media Group, 2020) and Tesla's new 10,000-acre claim on lithium clay deposits in Nevada (Tesla, 2020a).

GOVERNMENT ZEV COMMITMENTS

Analyzing the announced government passenger ZEV targets and existing regulations will allow the comparison of total global demands on ZEV deployment with other analysis below on raw materials and ramp-up of automaker production. Many governments have announced their goals for ZEVs to make up 100% of all new passenger vehicle sales in their jurisdictions. These announcements and the associated timelines are summarized in Table 2. As shown, 26 national and subnational governments have announced a 100% ZEV sales target by 2025–2050. Some jurisdictions are considering accelerating their timelines, and increasingly city governments also have goals for accelerating all zero-emission mobility.

Table 2. Government goals for 100% passenger zero-emission vehicle sales.

Announced target date for achieving 100% ZEVs	Jurisdictions
2025	Norway
2030	Denmark, Hainan, Iceland, Ireland, Netherlands, Slovenia, Sweden
2035	California, Québec, United Kingdom
2040	British Columbia, Canada, France, Taiwan
2050	Baden-Württemberg, Connecticut, Germany, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, Vermont, Washington

Other major markets also have near-term regulations and targets for ZEVs to make up a relatively substantial share of vehicle sales by 2030. China has a goal of 20% electric vehicle sales share by 2025 (Office of the State Council, 2020). In Europe, the 2025–2030 EU CO_2 emission standards for new passenger cars and light-commercial vehicles sets a 35% (30% in the case of light-commercial vehicles) sales target for electric vehicles by 2030 (Mock, 2019). In the United States, state ZEV regulations would deliver at least an 8% ZEV sales share by 2025, and a September 2020 executive order in California tasks the Air Resources Board with developing regulations requiring 100% passenger ZEV sales by 2035 (California Air Resources Board, 2020; California Executive Order N-79-20). Other major vehicle markets including India, Japan, and South Korea have announced targets for ZEVs to be about 20% to 33% of new sales by 2030 (Menon, Yang, & Bandivadekar, 2019; Japan Ministry of Economy, Trade and Industry, 2018; Park, 2019).

Based on the announced government ZEV targets and existing regulations summarized above, Figure 6 illustrates the annual ZEV sales in these markets. The figure includes the major markets of China, Europe (EU 28 + EFTA), the United States, India, Japan, Canada, and South Korea, which together accounted for about 80% of global passenger vehicle sales and 95% of global electric vehicle sales in 2019. As shown, annual ZEV sales in these markets reach around 10 million in 2025 and increase to about 28 million in 2030, and about 70 million in 2040. The grey wedge illustrates annual ZEV sales in the rest of the world, which increase from about half a million in 2031, to 3 million in 2040, and more than 8 million in 2050. This global growth in ZEVs represents about a 4% ZEV share of global sales in 2020, increasing to about 55% in 2035 and greater than 90% in 2050. The assumed overall growth in global passenger vehicle sales reaches about 90 million by 2050, from approximately 84 million in 2018. Because the global COVID-19 crisis has provided an unsteady environment for near-term automobile manufacturing and sales, the analysis assumes that about 65 million passenger vehicles are sold in 2020.

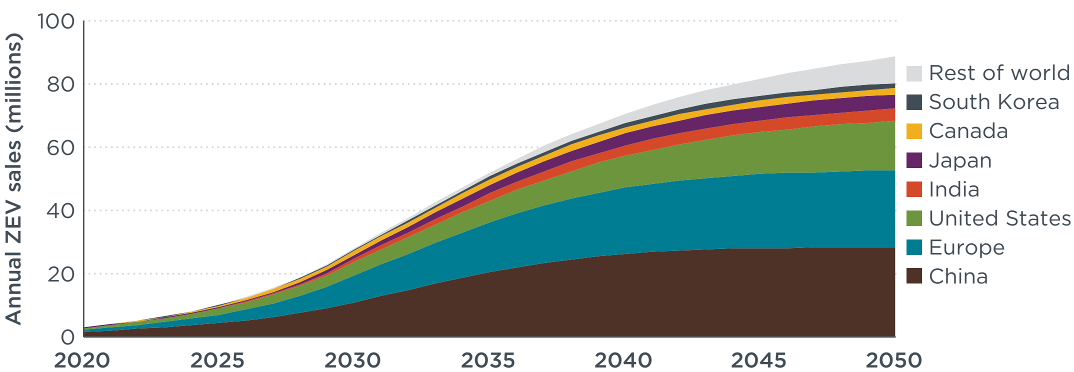

Figure 6. Annual ZEV sales based on announced government targets.

Several points provide more context on the long-term ZEV growth scenario shown in Figure 6. Although the overall trend is toward 90% of global sales being ZEVs, this trajectory includes and requires that many of the markets reach 100% ZEV sales well before 2050. As indicated above, among the largest markets with 100% ZEV targets before 2050 include California, Canada, France, the Netherlands, and the United Kingdom. To analyze annual ZEV sales from 2030 to 2050, we extend the analysis based on a hypothetical transition to all-ZEV sales in each of the major markets no later than 2050, consistent with long-term passenger vehicle decarbonization and climate change stabilization goals (Lutsey, 2015). The pace and scale of global ZEV market growth outlined here is a critical component of our global analysis of battery and raw material needs as described below.

REGIONAL ZEV SUPPLY IMPLICATIONS

One way to assess where the supply of ZEVs is being most quickly developed is to follow where the investments in ZEVs, batteries, and other supply chain components are going. Government electric vehicle targets and policies are driving automaker electric vehicle investments. Government volume targets and financial incentives have vested governments and manufacturers in developing the market and production facilities to support the transition (Lutsey et al., 2018). Figure 7 summarizes the nearly $300 billion in automaker investments from Table 1, broken down by the origin (x-axis) and destination (y-axis) of the investments across the major markets (based on Lienert & Chan, 2019). The circle size is proportional to the percentage of the cumulative 7.8 million electric passenger vehicles sales in each market from 2010 through 2019. China is the largest with about half of global electric vehicle sales through 2019, followed by Europe and the United States with about 25% and 20%, respectively.

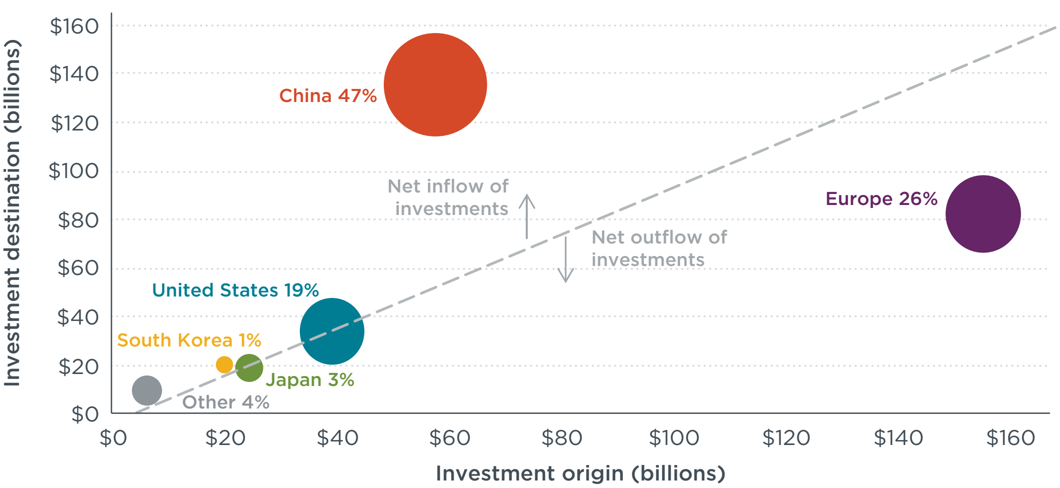

Figure 7. Announced industry electric vehicle investments by origin (horizontal axis) and destination (vertical axis) in major regions, with circle size proportional to the percentage of cumulative passenger electric vehicle sales.

The diagonal grey hashed line represents equal origins and destinations of electric vehicle investments. Markets that are above the line are receiving more investments relative to the investments originating there, whereas markets that are below the line are investing more in markets abroad relative to the investments destined there. In the upper left, China is poised for more investments than the other markets. In contrast, Europe is shown as largely having a net outflow of investments, indicating a lower level of investment in its ZEV supply chain. The United States and Japan are also shown with lower investment levels in their ZEV supply chain. Although China is more rapidly developing its ZEV supply chain, the location of a significant share of announced future battery manufacturing capacity is yet to be identified (see Figure 5), and the locations of much of the future ZEV production (see Figure 4) have largely not been specified. Overall, the investments appear to be accelerating; in 2019, investments totaling 60 billion euros for electric vehicles and batteries destined for Europe were announced, a 19-fold increase from 2018 (Bannon, 2020).

Beyond the global automaker investment analysis of Figure 7, several automaker statements reveal deeper insights regarding where their electric vehicles are made and sold. In terms of electric vehicle production, Volkswagen's announcement is the largest, and the company aims to construct eight manufacturing facilities across Europe, China, and the United States by 2022 to produce 4 million electric vehicles per year by 2028. More than half of these electric vehicles are destined for China, with about 25% destined for Europe, 10% to North America, and less than 5% to the rest of the world. Announcements by other automakers indicate a similar trend. Overall, industry announcements suggest the majority of electric vehicle supply is focused on China, followed by Europe and the United States. Although COVID-19 has provided an unsteady environment for near-term automobile manufacturing and supply, many automakers do not appear to have significantly amended their long-term plans for ZEV supply.

Table 3. Example automaker announcements for ZEV supply.

Automaker	Production announcements	Delivery announcements	References
Volkswagen	Eight modular electric drive toolkit manufacturing plants across Europe, China, and the United States by 2022. Produce 4 million electric vehicles per year by 2028.	Over 95% of electric vehicles sales through 2028 projected for China (60%), Europe (26%), and North America (11%).	Volkswagen, 2019a; Volkswagen, 2018; Kodjak, 2019
Toyota-Suzuki-Mazda-Subaru	2–3 million by 2025.	BEVs will first launch in China in 2020, followed by Europe, the United States, and elsewhere. Half of EV sales are destined for China, with the other half mostly in Europe and the United States.	Schmidt, 2019
Hyundai Motor Group	1 million electric vehicles annually by 2025.	Initially focus on key markets like Korea, the United States, China, and Europe by 2030. By 2035 expand to emerging markets like India and Brazil.	Hyundai, 2019; Jin & Lee, 2020
Kia	500,000 electric vehicles annually by 2026.	Prioritize EV deployment in markets with stronger fuel-efficiency standards, including Korea, North America, and Europe. Offer full EV lineup and reach 20% EV sales in these markets by 2025.	Kia, 2020
Ford	50,000 Mach-E electric vehicles will be produced at the North America facility in 2020.	Deliveries to Europe delayed due to COVID-19. 60% of first-year production units will be allocated to Europe to comply with CO_2 regulations.	Mach-E Forum, 2020; Berman, 2020; Dow 2019; Randall, 2019
Honda	Electrify two-thirds of global line-up by 2030.	Initial focus on Europe, where all mainstream models will be electrified by 2022. Driven by regulations, the market, and consumer behavior.	Honda, 2019
Fiat Chrysler	$22 billion to develop up to 30 nameplate hybrid and electric vehicles through 2022.	Focus on China as the region with the highest BEV sales shares. Focus on PHEVs in the U.S.	Fiat Chrysler Automobiles, 2018

Together, these announced automaker production developments influence the global and regional vehicle supply. Depending on automaker deployment decisions about their overall production volume and the number of target markets, there are often limitations in vehicle availability in the areas that are not prioritized. Based on electric vehicle sales through 2019, the collection of forward-looking statements in Table 3, and industry statements, automakers are targeting electric vehicle supply to the major markets with regulatory and consumer-support policies. Another example indicating how automakers prioritize markets with ZEV policy developments is Fiat

Chrysler's 2018 financial report, which lists compliance-focused vehicle sales initiatives by region and references regulatory measures as an underlying reason (Fiat Chrysler Automobiles, 2018). As Tom Gardner, senior vice president of Honda Motor Europe, describes, "The pace of change in regulation, the market, and consumer behavior in Europe means that the shift towards electrification is happening faster here than anywhere else in the world" (Honda Motor Europe, 2019).

Intramarket electric vehicle supply dynamics are further revealed by evaluating electric vehicle model availability and sales across the United States and Europe. Figure 8 illustrates the 2019 U.S. and Europe electric vehicle sales by automaker (vertical bars, left axis) and the number of metropolitan areas with electric models being made substantially available (data circles, right axis) by major automakers. The Europe data includes 16 of the largest vehicle markets in Europe, including Norway and the United Kingdom (Hall, Wappelhorst, Mock, & Lutsey, 2020). To determine whether electric models were made available in significant numbers, we use a threshold of there being at least 20 electric vehicle sales in a given year by each company across metropolitan areas. The automakers are listed from left to right based on 2019 electric vehicle sales.

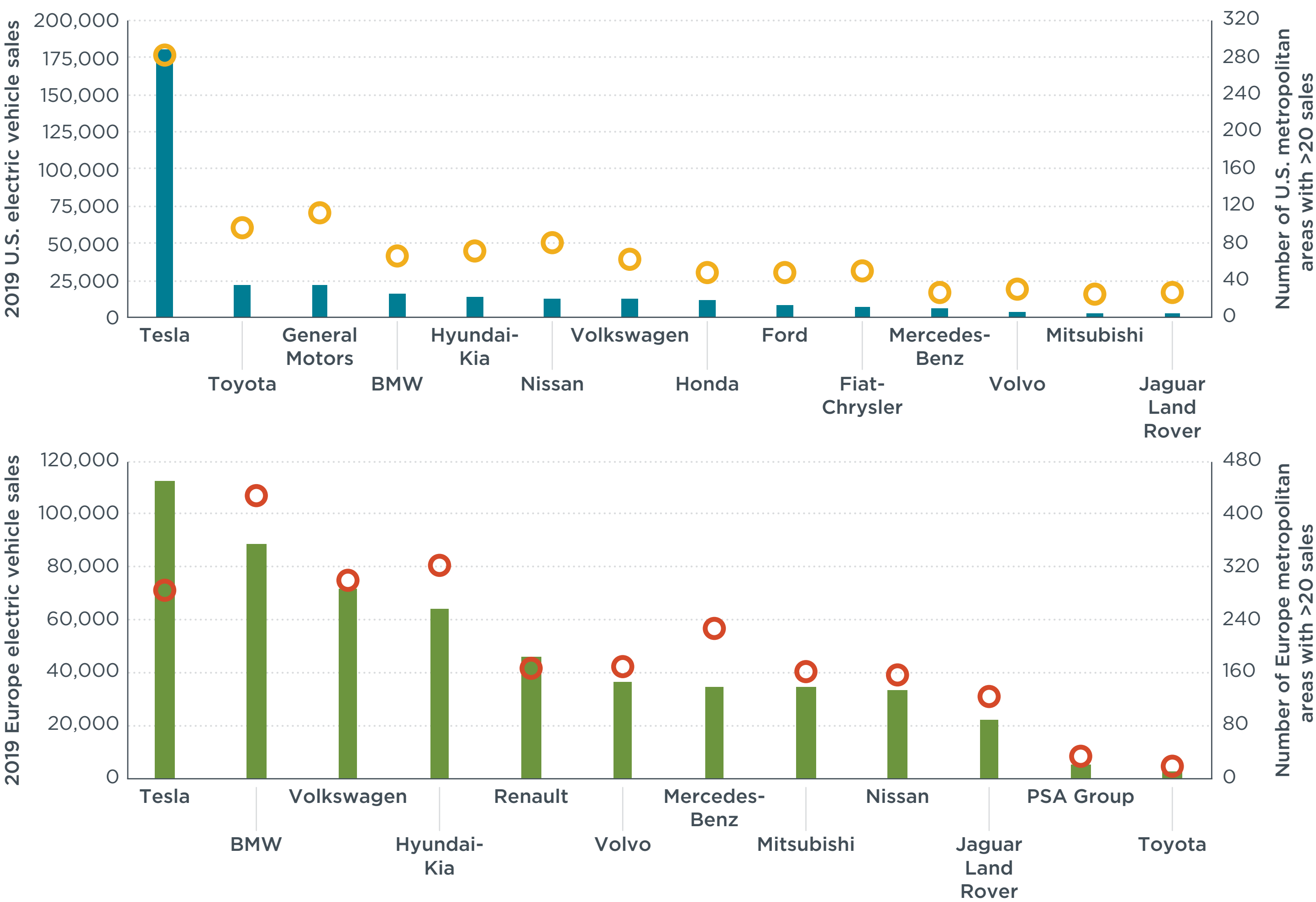

Figure 8. U.S. and Europe 2019 electric vehicle sales by automaker (bars) and number of metropolitan areas with substantial electric vehicle deployment by automaker (circles).

The figure shows a clear general trend. Companies with more electric vehicle sales have the ability to make their electric vehicles much more widely available across more metropolitan areas. In the United States, Tesla stands out with about seven times more electric vehicle sales than any other automaker, and Tesla sold more than 20 electric vehicles in about 280 metropolitan areas. This compares to other companies that deployed only 5,000 to 20,000 electric vehicle sales and have significant deployment of their electric vehicles in 25 to 110 metropolitan areas. In Europe, the four automakers with the most electric vehicle sales—Tesla, BMW, Volkswagen, and Hyundai-Kia—had substantial electric vehicle deployment across more than 300 metropolitan areas, whereas lower-volume companies typically supplied electric vehicles to half as many European local markets.

Overall, companies with fewer electric vehicle sales sell electric vehicles in fewer metropolitan areas. From this, we find that companies with the most electric vehicle sales are more geographically dispersed to where electric vehicles are supplied. Companies with less than 50,000 units per year in sales volume tend to be much more isolated and limited in where they supply vehicles. Lower volume and less geographic dispersion mean the supply of electric vehicles is more limited across the markets, in turn meaning narrower efforts on marketing, consumer awareness, or dealer training across markets. For example, in the United States, half of the population lived in areas that had access to fewer than 12 electric models in 2019, as compared to leading markets having access to 30–40 electric models (Bui, Slowik, & Lutsey, 2020). The broader implications of this relationship between production volume and local availability and supply of electric vehicles is further discussed in section five.

Tesla is an example of a company that has greatly expanded electric vehicle production. Its Fremont, California, factory has increased annual production volume from about 50,000 units in 2015 to 100,000 units in 2017 and more than 300,000 units in 2019. Over this same time, the company made decisions about where to supply vehicles in different markets. Through 2018, Tesla sold more vehicles in the United States. However, in 2019, as production volume increased and the U.S. federal income tax credit phased out, it shifted to specific markets in Europe with incentives (e.g., Norway, Netherlands, the United Kingdom) and also with pooling of CO_2 credits with Fiat Chrysler. As the company continues to grow and expand into more markets in higher volumes, Tesla is constructing manufacturing facilities in Shanghai and Berlin to more strategically manufacture vehicles in closer proximity to the major markets where the vehicles will be deployed.

ANALYSIS OF ZEV RAW MATERIALS AND COMPONENTS

This section assesses what meeting government and automaker goals for ZEV sales would mean for the future demand for key raw materials. It includes an overview of the key technical vehicle specifications and electric vehicle battery chemistries used in this analysis, which are used to assess the future global need for raw materials and battery capacity.

ELECTRIC VEHICLE TECHNICAL SPECIFICATIONS

Our analysis of raw materials needed for electric vehicle battery packs is based on a variety of assumptions related to technical vehicle specifications. Based on trends through 2019, the global electric vehicle market of battery electric vehicles (BEVs) is assumed to grow from 75% in 2020 to 80% by 2030 and 100% by 2050. In 2020, electric vehicle sales are split approximately evenly across small, medium, large, and light truck segments. By 2050, light trucks, which are primarily crossovers and SUVs, represent about 35% of electric vehicle sales globally. This is the result a continuing global trend toward greater SUV and crossover sales.

Although there will be many shorter- and longer-range BEVs across different markets over time, we assume the average real-world BEV electric range increases from approximately 190 miles in 2020 to 205 miles in 2050. We incorporate average electric vehicle energy efficiency improvements of about 0.6% per year, with efficiency improvements in electric components, aerodynamics, lightweighting, and tire rolling resistance. Overall, the average global electric vehicle energy efficiency generally remains roughly consistent at about 0.3 kilowatt-hours per mile (kWh/mile) from 2020 to 2050, due to the divergent trends of increased per-vehicle energy efficiency and the fleet shift to inherently less efficient larger electric vehicles. Combining these trends, the estimated sales-weighted average BEV battery capacity increases from 50 to 60 kWh from 2020 to 2050.

Lithium-ion battery packs are by far the most commonly used battery type in modern electric vehicles, representing more than 99% of the electric vehicle battery market from 2010–2019. Over this time, there have been significant technological advancements in lithium-ion battery performance, energy density, and cost; continued improvements are expected as a result of chemistry innovation, learning, and increased production volume (Berckmans et al., 2017; Li, Erickson, & Manthiram, 2020; Lutsey & Nicholas, 2019; Schmuch, Wagner, Hörpel, Placke, & Winter, 2018).

Lithium-ion battery packs offer several advantages over other common rechargeable battery counterparts, including lead-acid, nickel-cadmium, and nickel-metal hydride. One of the most important advantages of lithium-ion batteries for use in vehicles is their relatively higher energy density, which is a result of lithium being the lightest metal. Its relative electrochemical advantages include higher cell voltages, no required maintenance, and typically lower self-discharge rates when the battery is not in use. Yet there also are challenges: lithium-ion batteries are relatively fragile and require protections to prevent overcharge and manage temperature, and they have a somewhat lower cycle life compared to others like nickel-cadmium batteries.

Several distinct lithium-ion battery chemistries are used in electric vehicle battery packs. Global electric vehicle sales over 2010–2019 were dominated by four major lithium-ion battery chemistries: nickel-manganese-cobalt (NMC), nickel-cobalt-aluminum (NCA), lithium-iron-phosphate (LFP), and lithium-manganese-oxide (LMO).

About 70% of the battery packs in electric vehicles sold in 2019 were NMC, while NCA represented about 20%. The growth of NCA reflects the growth of Tesla, which represents more than 95% of NCA vehicle batteries deployed. In terms of total GWh in 2019, NMC was about 65% of the market while NCA was about 30%. The share of LMO batteries has been gradually declining, from about 33% in 2012–2014 to less than 5% in 2019. LFP technology has largely been developed and deployed in China.

Several NMC variants, including NMC-111, NMC-532, NMC-622, and NMC-811, have been deployed in electric vehicles. The numbers correspond with the relative ratios of nickel, manganese, and cobalt: NMC-111 is equal parts nickel, manganese, and cobalt, whereas NMC-532 has 5 parts nickel to 3 parts manganese and 2 parts cobalt. About half of NMC batteries in 2018 were NMC-532, followed by NMC-622 at 40%, and NMC-111 was about 10%. Overall, there has been a general industry trend to shift to higher ratios of nickel and less cobalt.

Lithium-ion battery chemistries have their own unique characteristics. Figure 9 shows the major chemistries and their relative performance across five key parameters: energy, power, cost, lifetime, and safety. As shown, NCA and NMC score the highest in terms of energy, whereas NCA also ranks high in terms of power, lifetime, and low cost. LFP scores highest in terms of safety and longevity. NMC shows the best balance in performance among all parameters, with high values for power, lifetime, and safety, despite somewhat higher cost than NCA. Broadly speaking, NCA and NMC batteries are typically used in long-range electric vehicles while LFP batteries are for shorter-range electric vehicles that require more frequent charging.

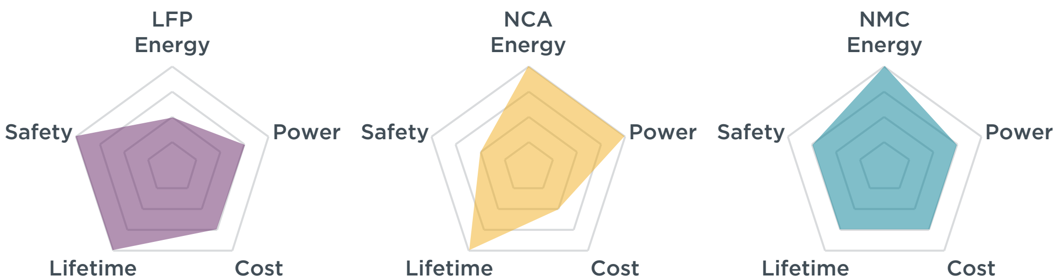

Figure 9. Major lithium-ion battery chemistries and their key performance indicators (adapted from Ding et al., 2019).

The NMC variants that are the most nickel-rich, such as NMC-622 and NMC-811, provide greater energy density (kilowatt-hours/kilogram) and lower costs, optimizing performance specifications like battery size and weight, vehicle range, and battery cost. Despite these advantages, high-nickel content in NMC-811 creates structural and chemical stability challenges, which raise the need for additional protections within the battery cells to avoid unwanted reactions. For these reasons, although NMC-811 is widely considered to be an improved near-term battery technology for electric vehicles, it is an emerging technology that is increasingly being commercialized by automakers and suppliers. Recent reports indicate that the new NMC-811 chemistry represented 12%–13% of electric passenger vehicle battery capacity in China in 2019 and 2020, up from nearly none in 2018 (Adamas Intelligence, 2019; LeVine, 2020). As outlined in the next section, this analysis assumes nickel-rich chemistries like NMC-811 will be more widely adopted in electric vehicle applications in the near future because of their energy and cost advantages.

FUTURE LITHIUM-ION BATTERY CHEMISTRIES

The analysis of future lithium-ion battery chemistries includes an assessment of lithium-ion battery chemistries, the evolution of global market shares into next-generation lithium-ion chemistries, and the tracking of key materials content in electric vehicle batteries.

Our analysis of the 2020–2050 global market share of electric vehicle battery chemistries and the metal content in each chemistry is based on several studies that evaluate existing and next-generation electric vehicle batteries. The studies consulted are Azevedo et al. (2018); Anderman (2019); Avicenne Energy (2017b); Baier (2019); Berckmans, Messagie, Smekens, Omar, Vanhaverbeke, and Mierlo (2017); Berman et al. (2018); BNEF (2019); Boyd (2019); CATL (2018); Dai, Kelly, Dunn, and Benavides (2018); Ding et al. (2019); Li et al. (2020); Massachusetts Institute of Technology (2019); Pillot (2019); Schmuch et al. (2018); Schuhmacher (2018); Total Battery Consulting (2019); UBS (2018); Wentker, Greenwood, and Leker (2019); and Yugo and Soler, (2019). As above, electric vehicle model, battery, and sales data from EV-Volumes (2020) were used to establish the 2017–2019 baseline trend, before estimating future battery market changes.

Figure 10 summarizes the global market share of electric vehicle battery chemistries from 2020 to 2035 used in this analysis, including NMC-111, NMC-532, NMC-622, NMC-811, NCA, other, and all next-generation. Other includes current LFP, LMO, LCO, and LTO chemistries that are in small fractions and appear to be phasing out. Next-generation batteries include lithium-ion chemistries identified in the research literature for their evolutionary improvements from NMC, LFP, and NCA (i.e., without the use of solid-state or other technologies at earlier development stages). These include high-voltage NMC and NCA; lithium-rich NMC, NMC-85, NCA-91; manganese-rich, ultra-high nickel; and advanced LFP (Berckmans et al., 2017; CATL, 2018; Li et al., 2020; Xinhua, 2019). The next-generation batteries often also include a partial shift from a graphite to silicon anodes to further improve specific energy. We assume that each next-generation chemistry represents a similar fraction of the overall next-generation battery market.

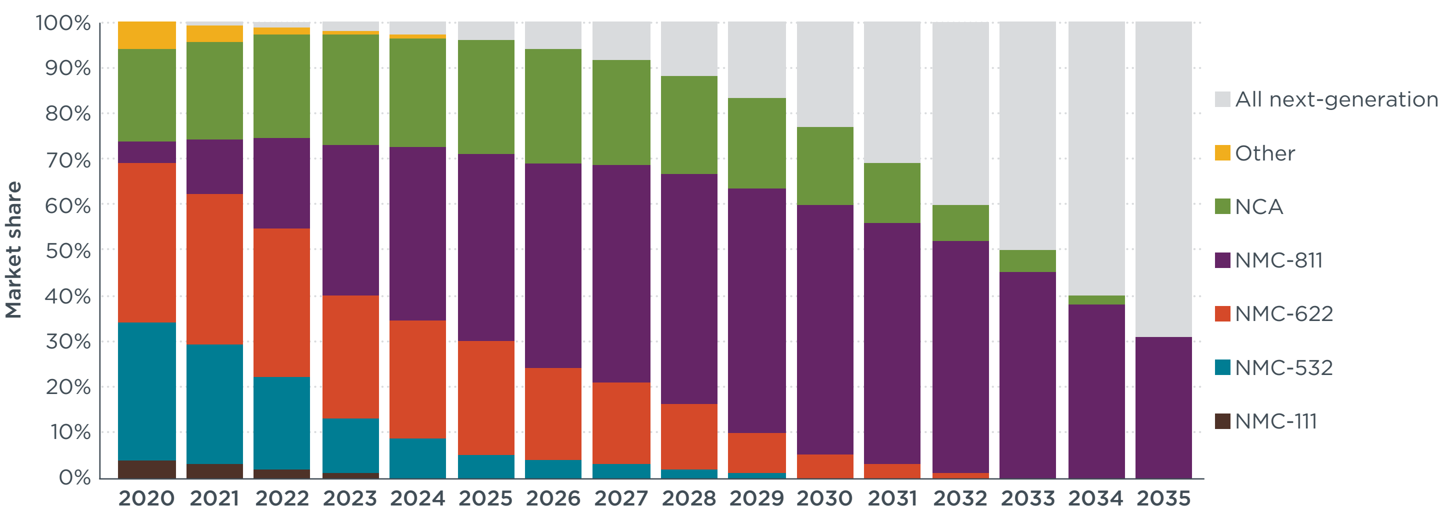

Figure 10. Electric vehicle battery chemistries assumed in this analysis.

The figure shows the evolution of batteries toward higher nickel content NMC, with NMC-811 increasingly replacing the lower-nickel NMC-532 and NMC-622 from 2020 to 2030. NCA batteries hold approximately 20% to 25% market shares until 2030. As shown, next-generation batteries begin to phase in reaching about 5% market share in 2025 and grow to half the battery market in 2033. Beyond 2035, the use of NMC-811 phases down to less than 10% of the market by 2040, replaced by a mix of next-generation battery chemistries, which are assumed to make up about 95% of the global battery market by 2040.

The future chemical composition of electric vehicle battery packs beyond 2030 is highly uncertain, and there are no known research studies that definitively assess next-generation electric vehicle battery pack chemistries beyond 2030. Opportunities remain for significantly improving lithium-ion battery technology, and some industry groups are working to develop next-generation solid-state battery technology. Immense challenges remain to the eventual commercialization of next-generation electric vehicle battery packs, and it is not clear if the needed technological breakthroughs will occur or which technologies might deliver the performance benefits that are sought. Some battery experts predict that solid-state batteries could move beyond research and development and prototype stages to high-cost, low-volume availability at the end of the 2020s; others see lithium-ion as the best available technology for the foreseeable future (Stringer & Buckland, 2019). Due to this uncertainty, this analysis does not depend on the commercial breakthrough of solid-state batteries.

Putting these chemistry shifts on a kilograms per kilowatt-hour (kg/kWh) basis provides context to these battery chemistry trends. Using NMC-622 as an illustrative example for 2020, we find there are about 0.12 kg/kWh lithium, 0.61 kg/kWh nickel, 0.19 kg/kWh manganese, and 0.20 kg/kWh cobalt. This means that a typical 250-mile range electric vehicle with a 60 kWh battery pack requires about 7.2 kg lithium, 36.6 kg nickel, 11.4 kg manganese, and 12 kg cobalt. These values are reduced by approximately 14% by 2030 for a same-sized 60 kWh battery pack primarily because of energy density improvements. On average the next-generation chemistries in 2030 have 86% less cobalt, 64% less manganese, and 39% less nickel than the 2020 values for NMC-622, primarily because of energy density improvements and shifts to lower-cobalt chemistries. Some of the next-generation technologies see relatively greater or lesser material needs (e.g., next-generation LFP uses no cobalt, manganese, or nickel; NMC-85 has high nickel content and low manganese and cobalt). A summary of the 2030–2040 sales-weighted cathode material content of next-generation chemistries is shown in the Appendix.

RAW MATERIAL AND BATTERY PACK DEMAND

Based on the electric vehicle scenario (see Figure 6) and the share of battery chemistries used in electric vehicles (see Figure 10), Figure 11 summarizes the amount of battery-grade materials required to supply a scenario increasing to 28 million annual electric vehicle sales in 2030 and to 89 million in 2050. The figure shows the demand for several key materials: lithium, manganese, cobalt, phosphorous, iron, nickel, and graphite. As shown, 28 million annual electric vehicle sales in 2030 will require about 100,000 metric tons of lithium, 70,000 metric tons of manganese, 82,000 metric tons of cobalt, 9,000 metric tons of phosphorous, 16,000 metric tons of iron, 600,000 metric tons of nickel, and 225,000 metric tons of graphite. Although not shown, aluminum and copper are important for battery housing and anodes; about 2.9 million metric tons combined per year will be required by 2030. In 2050, about 90 million annual electric vehicle sales will require about 335,000 metric tons of lithium, 315,000 metric tons of manganese, 135,000 metric tons of cobalt, 130,000 metric tons of phosphorous, 240,000 metric tons of iron, 1.7 metric tons of nickel, and 900,000 metric tons of graphite.

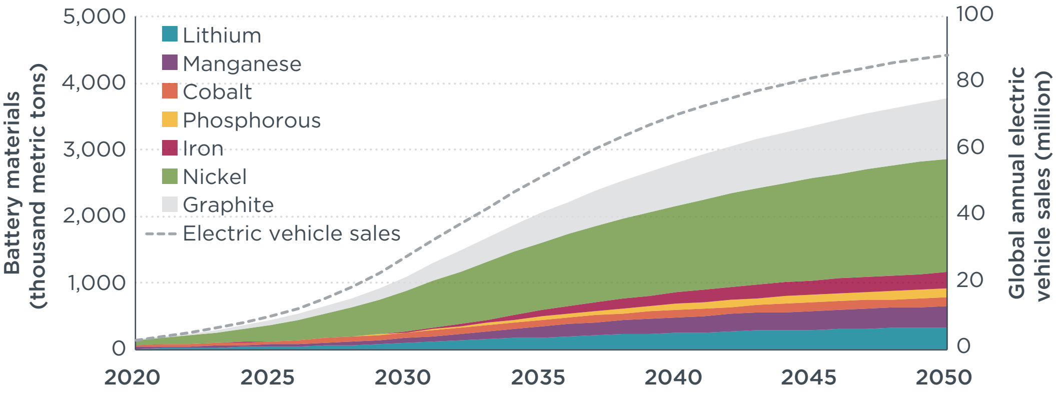

Figure 11. Materials needed to supply electric vehicle batteries and global annual electric vehicle sales from 2020 through 2050.

Overall, from 2020 to 2050, annual electric vehicle sales increase by a factor of about 30. The increase in material needs is sensitive to the mix of future battery chemistries. Over this same period, lithium demand increases by a factor of about 23, whereas nickel demand increases by a factor of about 26. In contrast to those increases, manganese and cobalt demand increase by factors of about 13 and 6, respectively, because of the shift to higher nickel and lower cobalt- and manganese-content batteries. Shifts to more advanced battery chemistries and technological advancements in energy density are leading to less material being needed per vehicle. The demand for battery-grade materials shown in Figure 11 is without recycling, which is assessed below.

Public announcements for new and expanded raw material production capacity are accompanying this increase in material demand for lithium and cobalt. Lithium production projects in Chile, Australia, Argentina, Canada, and Nevada have been announced by major companies including SQM, Albemarle, Lithium Americas Corp, and others (Lombrana, 2019); the new and expanded production capacity exceeds 40,000 metric tons through 2022. From the ZEV transition scenario previously presented, annual lithium demand increases by about 15,000 metric tons from 2019 through 2022 to about 23,000 metric tons. Although the announced production exceeds the growing demand from passenger ZEVs through 2022, relatively low lithium market prices in 2019 and 2020 are hindering the business case for new lithium production and some projects have been delayed. The public announcements for expanded cobalt production indicate about 24,000 metric tons of additional supply through 2023, mostly in the Democratic Republic of the Congo (DRC), North America, and Australia. The preceding ZEV demand side analysis indicates an increase in cobalt demand of about 22,000 metric tons over this same period, suggesting that new supply will slightly exceed demand unless more cobalt supplies are developed.

To provide the broader context, the demand for passenger electric vehicle batteries is included with the overall potential lithium-ion demand from other sectors and the expected increase in battery capacity. Figure 12 shows the global supply and demand of lithium-ion battery capacity from 2019 through 2025. The supply of global battery production capacity is shown by the orange hashed line and is based on the industry announcements summarized in Figure 5. The wedges show battery demand from several applications, including passenger electric vehicles (blue), and non-light duty vehicle applications (black), including delivery, drayage, and long-haul trucks and buses. The figure shows that the projected global production capacity will meet the projected total demand. By 2025, global demand is about 900 GWh whereas production capacity is about 25% greater than this value. For any given year in the 2019 to 2025 time frame, supply exceeds demand by about 20% to 40%. On average over this period, production capacity exceeds demand by about 30%.

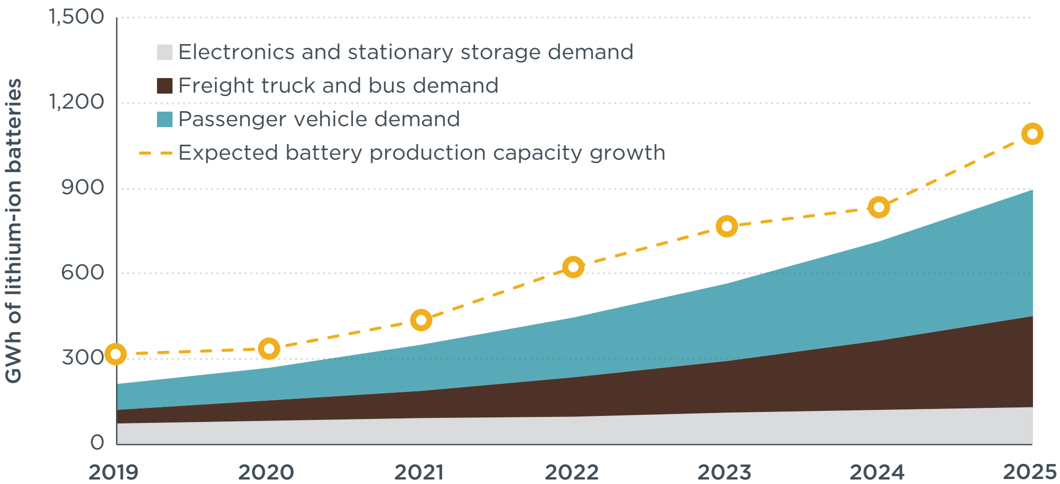

Figure 12. Global production of lithium-ion battery capacity needed to supply the transition to electric vehicles, and estimated demand for transport and nontransport applications.

Several additional points help provide context to the analysis behind Figure 12. The analysis of passenger electric vehicle battery demand is based on the growth curve shown in Figure 6 and technical specifications previously outlined, specifically the gradual increase in per-vehicle battery capacity from about 40 kWh to 45 kWh. Consumer electronics and stationary storage applications are assumed to increase by 10% per year. The analysis of nonpassenger vehicle applications in this time frame is primarily based on growth of electric delivery vehicles and buses reaching 10% and 15% of global sales shares, respectively, whereas new electric drayage and long-haul vehicles represent about 1% of the market by 2025. Further analysis of battery demand, chemistries, and resource needs for trucks, buses, and other sectors from 2025 and on warrants further analysis but is beyond the scope of this paper.

Although it is considerably more speculative, an extension of this analysis beyond 2025 through 2035 helps provide a sense of scale for the industrial buildup needed to support this supply chain. This analysis indicates that annual lithium-ion battery demand grows to about 2,400 GWh by 2030 and about 4,700 GWh by 2035. This is a compound annual growth rate of approximately 20% from 2020 to 2035. If each new battery plant has an annual production of about 35 GWh per year (Tesla, 2017), we can roughly estimate the number of such “gigafactories” needed globally. By 2030, there would need to be approximately 35 new such gigafactories, beyond the 1,100 GWh in battery production already slated to be in place by 2025. By 2035, assuming battery plants expanded to 50–60 GWh per year, about 65 new gigafactories are needed globally, beyond those announced for 2025, for this level of battery production.

Equating the passenger vehicle battery production to monetary terms gives an approximate valuation of the automaker battery procurement necessary to support electric vehicle deployment through 2030, shown by the blue wedge in Figure 12. As global annual battery demand from electric passenger vehicles increases 14-fold from about 90 GWh in 2019 to about 1,300 GWh in 2030, the total value of global battery procurement increases substantially. The annual value of battery procurement exceeds $40 billion in 2025 and $90 billion in 2030. The cumulative value of battery procurement in the first five years (2021–2025) is more than $150 billion and in the first 10 years (2021–2030) is more than $500 billion. This is based on the increase in passenger electric vehicle battery demand, as previously described, and continued reduction in battery pack costs from about $156 per kWh in 2019 to $70 per kWh in 2030 (Lutsey & Nicholas, 2019).

COMPARISON OF RAW MATERIAL AVAILABILITY AND DEMAND

The global demand resulting from the transition to passenger electric vehicles, as shown in Figure 11, can be compared to the global availability of raw materials based on available data. We assess raw material availability as the amount of known reserves based on the latest available research literature and government data. Reserves are a subset of the estimated global total resources that are discovered and considered economically recoverable at the time of classification (U.S. Bureau of Mines and U.S. Geological Survey, 1976). Continued advancements in mining technology and the market price of raw materials can increase the size of known reserves.

As reported by the United States Geological Survey (2020), the 2020 global known reserves include approximately 17 million metric tons of lithium, 89 million metric tons of nickel, 810 million metric tons of manganese, 7 million metric tons of cobalt, and 300 million metric tons of graphite. Comparing the known reserves with the cumulative passenger electric vehicle material demand from the scenario shown in Figure 11, cobalt is the most limiting factor. From 2025 to 2035, the cumulative use of cobalt as a percentage of known reserves increases from about 3% to about 14%. The cumulative use of lithium, nickel, manganese, and graphite as percentages of known reserves are relatively less. From 2025 to 2035, cumulative demand for lithium and nickel increase from about 1% of known reserves to about 8%. Cumulative use of manganese and graphite is less than 1% of known reserves.

Although the raw material demand for ZEVs by 2035 is far below known reserves for graphite, manganese, lithium, nickel, and cobalt, sustained expansion of global mining and refining capacity remains important. Continued expansion is needed to provide sufficient volumes of battery-grade materials for battery manufacturing. It is unclear whether the pace of the expanded mining and production of battery-grade precursors will precisely meet near-term demand for battery manufacturing. Compared to the cell manufacturing investments, upstream investments in mining, ore extraction and processing, battery-grade material refining, and production of active materials are relatively unknown. Low market prices could slow upstream investments. Experts at Wood Mackenzie predict a need for automakers to increasingly invest in nickel, cobalt, lithium, and graphite mining and refining to secure their supply (Wood Mackenzie, 2020). Some automakers have begun to do so, as well as diversifying their battery technologies. Timing is an additional challenge because new mines can take a decade to move from exploration to eventual operation, leading to short-term battery material shortages (Benchmark Mineral Intelligence, 2020).

The global distribution of known electric vehicle raw material reserves has important implications on global supply dynamics. Materials including lithium and cobalt have been identified by governments as strategically important as well as critical due to potential supply risks (Leon & Miller, 2020). Among others, the United States lists lithium, cobalt, manganese, graphite, and rare earth elements as "critical" raw materials for national security and the economy (United States Geological Survey, 2018). The European Commission's Strategic Action Plan on Batteries report lists lithium, nickel, cobalt, manganese, and graphite as essential battery raw materials (European Commission, 2019).

Figure 13 illustrates the global distribution of known reserves and the share of 2019 mining production for several key raw materials: lithium, nickel, cobalt, graphite, and rare earth metals. The data circles indicate the relative share of mining production in 2019 (left) and the relative share of known global reserves as of 2020 (right). The different colors represent different raw materials (i.e., lithium is blue, cobalt is red, nickel is green, graphite is grey, rare earths are orange). The areas with the largest data circles are those that have the greatest relative mining production (left), reserves (right), or both. The DRC stands out with more than 70% of cobalt mining production in 2019 and about half the global reserves. For lithium, Australia and Chile stand out as major areas for mining production, followed by China and Argentina. About half of the world's known lithium reserves are in Chile. China stands out as home to more than 60% of the global mining production of graphite and rare earth metals, and significant known reserves of these materials are in China. Major areas for nickel include Australia, Canada, Indonesia, and the Philippines.

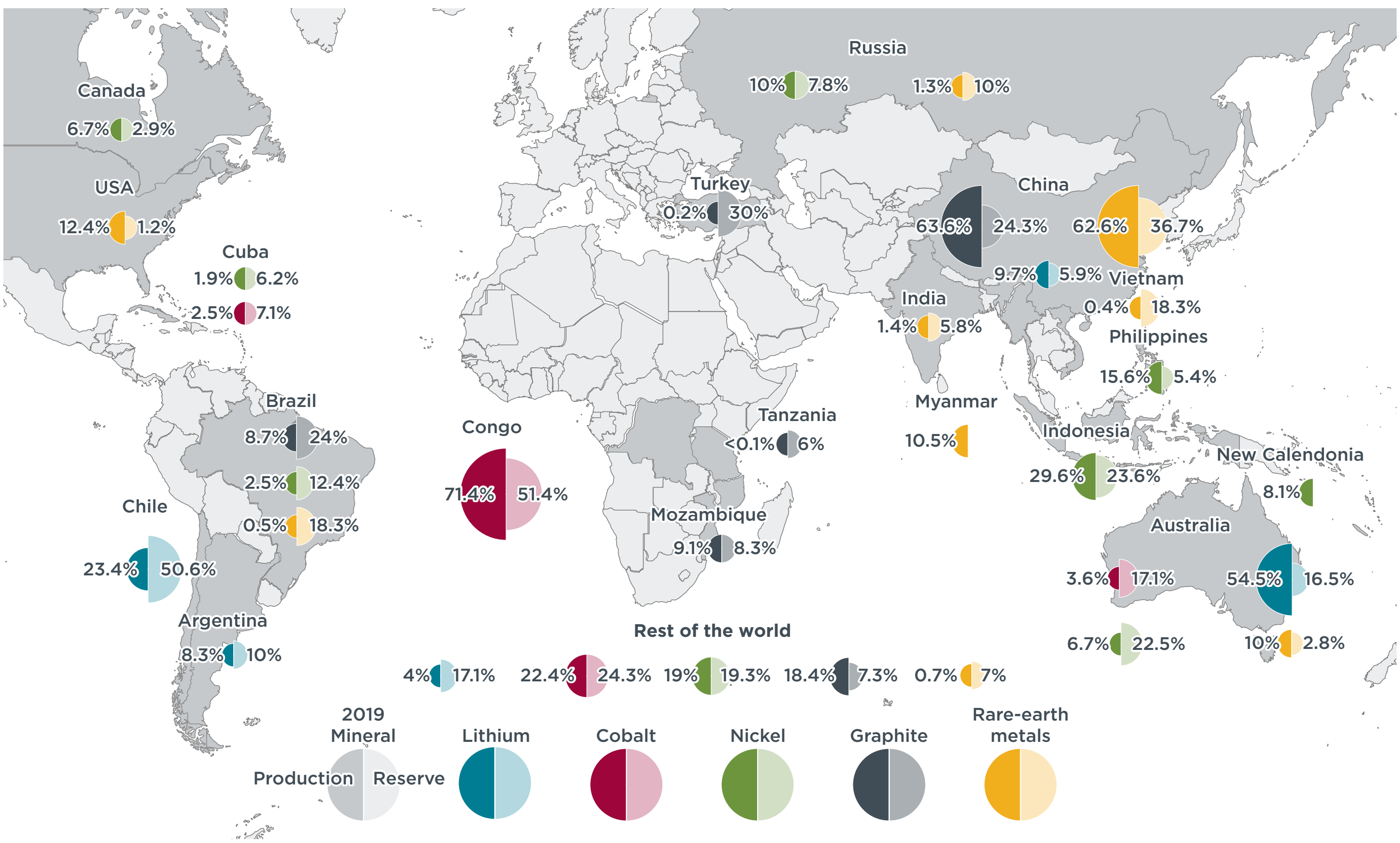

Figure 13. Global distribution of known reserves as of 2020 and 2019 mining production.

The battery chemistries being produced in each region could also have implications on raw material demand and global distribution. From 2010 through 2019, China produced about 50% of the world's NMC batteries in passenger vehicles; South Korea produced about 20%, and Europe and Japan each produced about 10%. Appendix Table A1 shows that NMC batteries typically use more cobalt than the other chemistries, use more manganese than NCA or LFP, and are relatively high in nickel content. Of the approximately 1 million electric vehicle NCA batteries produced from 2010 through 2019, about half were produced in Japan and half in the United States; NCA batteries have high nickel content and also require more cobalt than LFP or LMO. China and South Korea are the main producers of LFP batteries, which have high phosphorous and iron content.

Although not shown in Figure 13, the global distribution of material chemical refining and battery cathode and anode production also have important supply implications. The global distribution of battery-grade material production often differs from the distribution of raw material mining. Figure 13 shows that half the 2019 mining production of lithium was in Australia, followed by Chile (about 23%), China (about 10%), and Argentina (about 8%). In contrast, more than half of the 2019 lithium chemical supply was in China, followed by Chile (27%) and Argentina (10%) (Benchmark Mineral Intelligence, 2020). In terms of processing and refining, China is home to more than half of the world's capacity for processing and refining lithium and nickel, 80% for cobalt, 90% for manganese, and 100% for graphite (Securing America's Future Energy, 2020). China's role in global cathode and anode production is similarly significant, at about 65% and 80%, respectively. Some experts predict that most upstream battery-grade material and cathode supply in 2030 will continue to come from China (Benchmark Mineral Intelligence, 2020).

The ZEV supply chain is global and complex. Most electric vehicles are manufactured in China, Europe, and North America. Most electric vehicle battery packs are manufactured in China, Japan, South Korea, Europe, and the United States. Most of the 2019 production of cobalt was in the DRC, lithium in Australia and Chile, nickel in Southeast Asia, and graphite and rare-earth metals in China. Trade networks link battery production facilities with the upstream raw material production across continents. These ZEV supply trade networks are influenced by geopolitics and other factors. Although there is a mismatch between reserves and production from Figure 13 and the production of vehicles and batteries in Figure 2, companies are setting up production facilities in proximity to the mining of raw materials to localize supply chains. This is best evidenced by the BMW-Northvolt-Umicore collaboration to create a closed loop battery materials supply chain in Western Europe (Benchmark Mineral Intelligence, 2020); BYD's new 24 GWh battery factory in Qinghai, where more than 80% of China's lithium is located (Huang, 2018); Tesla's new 10,000-acre claim on lithium clay deposits in Nevada (Tesla, 2020a); and more generally Japan- and South Korea-based companies moving battery cell production to China.

OTHER CONSIDERATIONS

We explore several other considerations in our analysis of ZEV raw materials and components. The following paragraphs discuss factors associated with the global ZEV supply chain, including price fluctuations of key materials; auto industry resource management and alternative materials; and environmental, political, and humanitarian concerns in the ZEV supply chain.

Historic price fluctuations of key ZEV materials. Questions about the price volatility of cobalt and lithium arise in discussions of global ZEV supply. Cobalt in particular has a history of price volatility, experiencing two- to six-fold near-term price spikes during the 1970s, 1990s, in 2008, and in 2018. This volatility is linked with political, fiscal, and production instability in the DRC, and the mining conditions and associated extraction can vary widely. From mid-2018 to mid-2020, cobalt prices have decreased by approximately 70%. Although global cobalt production is primarily in the DRC, price signals in the market spur new capital and supply developments. This can bring more diverse geographic production of cobalt and can lead to improved price stability (Fu et al., 2020). We note that outside of the DRC, cobalt is a byproduct of nickel and copper mining and thus cobalt prices are linked to those of nickel and copper and could potentially pose as a geological constraint. In addition, advancements in battery recycling and the shift to lower- and zero-cobalt battery chemistries reduce the risk of high prices and diversify electric vehicle material demand.

For lithium, historic inflation-adjusted prices were relatively stable from 1970 to the late 1990s, and declined until 2010, driven by shifts in global production to South America in the late 1990s and continued with greater global exploration and production (United States Geological Survey, 2013). More recently, battery-grade lithium prices increased two-and-a-half-fold from 2015 to 2018 as global demand rose above supply. Prices fell in 2018 as global supply exceeded demand. Prices continued to fall in 2019 due to global overproduction, and several industry groups postponed plans for expansion (United States Geological Survey, 2020). It is noted that lithium prices that are published on a lithium-carbonate-equivalent basis do not account for major price differences between lithium carbonates and lithium hydroxides of technical or battery grades, and thus do not necessarily reflect battery material market dynamics. Just as price spikes influence industry actions for expanded capacity, price drops can pause plans for new exploration and production.

Despite this price volatility, the industry average price of electric vehicle battery packs has decreased from more than $1,000 per kWh in 2010 to about $140 to $160 per kWh in 2020. Even with a massive increase in battery demand for power electronics at the same time, the near-term raw material price volatility has had minimal impact on electric vehicle battery prices, which are typically determined on longer-time frame investments and contract agreements. Nevertheless, cobalt and lithium volatility can impact the upstream business case of automakers, battery suppliers, and mining companies. Some experts suggest that raw material costs could limit further battery price declines below $150/kWh based on 2019 battery chemistry and the cost of raw materials (Argus Media Group, 2019b).

Industry has responded to market signals by ramping up or delaying production capacity to balance the global supply with demand. Because the process of building a new mine and refining the ore into battery-grade materials typically takes five to 10 years, delays in 2020 impair the capacity for global supply to meet projected demand for battery-grade materials over the next decade. For this reason, if low market prices result in delays in new exploration and production, government funding or incentive programs may be needed to strengthen the business case and help ensure new projects come online.

Auto industry resource management. The auto industry has a history of weathering supply disruption and resource scarcity and has done so in a variety of ways: substituting scare resources with alternative materials, more efficient use of available resources, increasing recycling, and forging strategic partnerships. These provide examples of approaches that are being explored and implemented for the critical electric vehicle materials.

Several examples of responses demonstrate the strategic reactions from the auto industry. One example is related to scarcity of the polyamide 12 plastic, which is a special heat-resistant plastic needed for many engine components. Scarcity of this plastic in 2012 led to an emergency industrywide response to identify and substitute alternative materials (Tullo, 2013). Incremental improvements leading to more efficient use of materials continue across the auto industry. Automakers are proactively undergoing research and development to reduce the use of critical metals. Toyota developed an electric motor that reduces the need for rare earth elements by more than 50% (Toyota, 2018). At various stages of emission-control regulations, automakers faced higher platinum, palladium, and rhodium prices for their catalytic converters. This pushed companies to innovate with reduced engine emissions, reduced catalyst loading, different chemistries, and new catalyst designs—as well to hedge on future metal prices.

Recycling and new strategic partnerships can also alleviate issues surrounding resource scarcity. The vast majority of vehicles that reach end-of-life in the United States are recycled, recovering about 86% of vehicle materials (Steward, Mayyas, & Mann, 2019). Aluminum and lead-acid batteries are vehicle components with some of the highest recycling rates at 91% and 99%, respectively (Kelly & Apelain, 2016; United States Environmental Protection Agency, 2019). The historical recycling of lead-acid batteries is driven by economics from the higher relative value of retrieving the lead from scraped vehicles versus from natural materials. Environmental regulations in the 1990s improved the recycling rate from around 70% in the 1980s to over 90% (United States Environmental Protection Agency, 2019). Strategic partnerships are common across the industry. Toyota, for example, has long engaged in a joint-venture with major lithium producer Orocobre and has collaborative projects with rare earth companies to hedge against supply risk (George, Schillebeeckx, & Liak, 2015; Orocobre Limited, 2013).

Environmental, political, and humanitarian concerns in the ZEV supply chain. The extraction of natural resources has always been accompanied by environmental, political, and humanitarian concerns, and the impacts vary based on local regulations and politics. Combustion vehicles fueled by refined oil are associated with problematic upstream practices, including polluting extraction technology in sensitive areas, severe human-rights abuses, and corruption; similarly, the mining of metals is associated with human rights issues often linked to deeper governance challenges and corruption (Elkind, Heller, & Lamm, 2020). Resources needed for renewable technology tend to be more evenly distributed than fossil fuels, leading to lower risk of geopolitical conflicts over valuable locations (Overland, 2019). Extraction of raw materials in the ZEV supply chain can provide economic opportunities in material-rich countries, but proper governance and accountability structures are needed to ensure these opportunities are in the public interest.

Of the materials in the ZEV supply chain, cobalt is associated with the greatest humanitarian and governance risks. The DRC is home to about half of the global cobalt reserves and more than half of global extraction in 2019. Unregulated artisanal cobalt mining in the DRC is associated with unsafe mining conditions, child labor, and environmental pollution. Corrupt government practices have led to little safety, labor, or environmental enforcement and accountability, and the financial benefits from cobalt mining are diverted from the public interest (Callaway, 2018). Increasingly, auto companies are adopting zero-tolerance policies for battery procurement to ensure cobalt is sourced from practices that avoid such issues. Volkswagen, for example, has formed a strategic partnership to audit material and battery suppliers for compliance with safety, labor, and environmental protections (Volkswagen, 2020).

In addition to local environmental concerns regarding mining practices, the ZEV transition raises questions about the upstream greenhouse gas (GHG) emissions of electric vehicles, particularly from battery manufacturing. GHG emissions from battery manufacturing can result in higher vehicle manufacturing emissions, but these are "paid back" in two years of vehicle use under the European average electricity grid mix (Hall & Lutsey, 2018). In China, about 40% of all GHG emissions associated with battery manufacturing are from electricity consumption (Hao, Mu, Jiang, Liu, & Zhao, 2017). As a result, grid decarbonization is the key to reducing electric vehicles' production and vehicle use-phase emissions.

Industry developments are also contributing to more sustainable vehicle and battery manufacturing. Volkswagen has reduced per-vehicle manufacturing emissions and has a long-term for vision for zero-impact factories (Volkswagen, 2019c). Tesla aims for its Nevada Gigafactory to be net zero energy upon completion (Tesla, 2020b). BMW has agreements with battery suppliers to only use renewable energy for cell production (BMW Group, 2020). Northvolt's Sweden Gigafactory will use 100% renewable energy (European Commission, 2020). Additional efforts to identify and source raw materials from the production facilities and regions that have environmental regulations in place can further minimize emissions (Kelly, Dai, & Wang, 2020).

Improving environmental and social conditions, especially in source countries, is key to improving the reliability and integrity of the supply chain (Öko-Institut, 2017). Increased government and societal awareness around these issues has led to greater efforts to mitigate them. Continued promotion of international cooperation and adoption of due diligence practices is needed. More responsible raw material sourcing, use of renewable energy in manufacturing processes, and greater material recovery and recycling at end of life will support a more sustainable and ethical supply chain (Transport & Environment, 2019b). Transparency and traceability will help ensure that every step in the battery supply chain adopts the existing best practices in battery supply sustainability and responsibility.

Practices and principles for improved tracking of these battery issues are emerging. The World Economic Forum's Global Battery Alliance outlines 10 key principles for a sustainable and responsible battery supply chain, which are broadly categorized by establishing a circular battery value chain, establishing a low-carbon battery economy, and safeguarding human rights and economic development (World Economic Forum, 2020). At the same time, developments in the auto industry can lead to more humane alternatives through technological progress and materials substitution, including the shift to lower- and zero-cobalt batteries such as the next-generation LFP by Tesla and CATL and the cobalt-free NMx chemistry by SVOLT (SVOLT, 2020). Greater battery recycling capability, addressed below, can significantly reduce the need for additional extraction.

MITIGATING ZEV SUPPLY ISSUES

This section discusses the potential opportunities for mitigating ZEV supply issues. It explores the potential for battery recycling to minimize continued extraction of critical raw materials, investigates global ZEV supply shifts, and discusses how policies can impact industry decisions and the opportunities for policy to reduce the associated ZEV supply barriers.

BATTERY RECYCLING

In conjunction with the shift to more advanced battery chemistries with lower and zero-cobalt, developments in battery recycling can reduce the demand for new extraction of cathode raw materials and mitigate bottlenecks and price volatility (Öko-Institut, 2017). Although the volume of end-of-life electric vehicles is very small, multiple lithium-ion battery recycling processes exist. These facilities primarily recover high-value materials like cobalt and nickel (Church & Wuennenberg, 2019). There was approximately 94,000 tons of lithium ion battery recycling capacity in 2016, representing about 20% of manufacturing that year (Mayyas, Steward, & Mann, 2018). There are at least 10 major recycling facilities in operation across Asia, Europe, and North America.

Typical lithium-ion battery recycling includes three processes: disassembly, mechanical or thermal pretreatment separation, and hydrometallurgy chemical treatment (Leon and Miller, 2020). The recycling efficiency is determined by the collection rate of end-of-life batteries and the recycling efficiency (Lebedeva, Di Periso, & Boon-Brett, 2016). The lithium-ion battery collection rate is estimated to be around 15% to 25% (Larouche et al., 2020), and the recycling efficiency of battery cell materials ranges from about 72.5% to 80% depending on the separation process (Leon & Miller, 2020). Despite the relatively low collection rate, recycling is often desirable compared to processing the materials from original ore because the concentration of the materials in battery packs is often 10 times greater than that of the original ores (Leon & Miller, 2020). The economic case for battery recycling is linked to prices of battery-grade materials. Vertical integration to link recycling facilities with producers of active battery materials can strengthen financial viability.

Global battery recycling facilities and their capacity will need to ramp up significantly over the next decade to keep up with the pace and scale of electric vehicle market growth as more electric vehicles reach end-of-life. Driven by economics and regulations including the European directive on waste batteries and end-of-life vehicles, developments around recycling capacity are strongest in Europe and China, which represent about 50% and 33% of global capacity, respectively (Steward et al., 2019). The European Union is working to propose an updated legal regulatory framework that specifically addresses sustainability and end-of-life requirements for electric vehicle batteries (Frédéric Simon, 2020). Efforts to boost recycling capacity are underway, as indicated by recent developments by Tesla, Volkswagen, Umicore, and Primobius (Tesla, 2019; Volkswagen, 2019b; Umicore, 2019; Primobius, 2020).

To understand how improvements in global recycling capacity might reduce raw material demand, a case where lithium-ion battery recycling capacity increases by 20% per year through 2030, and then 15% per year after that, is analyzed. The analysis is based on a vehicle stock-turnover model of typical light-duty vehicle survival rates (Davis & Boundy, 2020). We assume that, on average, 60% of electric vehicle batteries go into second-life applications such as stationary storage for 10 years before becoming available for recycling. Of the remaining vehicle batteries that do not go to second-life applications, the battery collection rate from retired vehicles is assumed to increase from 20% in 2020 to 90% by 2030, and remains so through 2050. As these processes develop, it is important that the collection rate of end-of-life electric vehicles and their batteries is linked to the value of their components. The material recycling efficiency increases from 72.5% in 2020, based on Leon and Miller (2020), to 90% from 2030 (Umicore, 2019; Sato & Nakata, 2020).

Figure 14 shows the amount of materials needed in a scenario with greater recycling capacity, and the percent reduction compared to the no-recycling case shown in Figure 11. The figure shows the amount of materials for lithium, manganese, cobalt, and nickel. Iron, phosphorus, and graphite are not shown due to their much higher flows throughout the economy already, and developments surrounding graphite recycling have been limited due to its lower recovery value and global abundance (Harper et al., 2019; Mayyas et al., 2018). As shown, the annual need for materials peaks around 2040, when about 1,600 metric tons are needed for lithium, manganese, cobalt, and nickel combined. As shown by the orange hashed line, compared to a no-recycling case, the raw material needs are reduced by about 3% by 2030, 6% by 2035, 15% by 2040, and 40% by 2050. These developments would substantially reduce the need for additional extraction of critical materials.

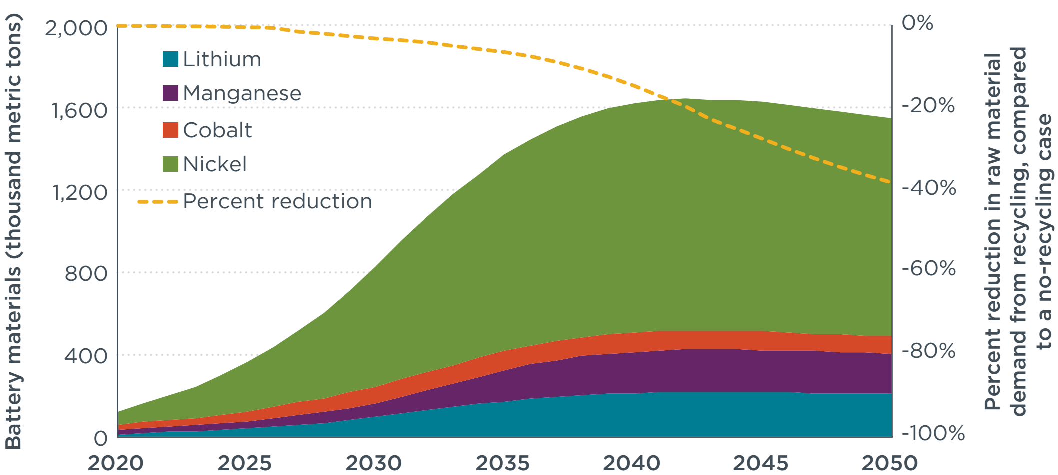

Figure 14. Raw materials needed to supply electric vehicle batteries with recycling, and the percent reduction in raw material demand from a no-recycling case.

Several additional points help to put the global recycling case in Figure 14 in context. Global electric vehicle sales growth outpaces the electric vehicles retired each year in the vehicle fleet stock-turnover model. In 2035, the number of end-of-life electric vehicles is about 10% of the number of new electric vehicle sales. By 2050, that value is about 55%. By assuming that 60% of the batteries in end-of-life electric vehicles are initially used in second-life applications, the total battery capacity that is available for recycling is reduced by about 20% in 2030 and 8% in 2050. The analysis does not include battery manufacturing scrap; incorporation of material from battery manufacturing scrap would reduce the need for additional mining from the recycling case. Beyond 2050, the raw material needs compared to a no-recycling case continue to be reduced as a greater number of electric vehicles reach end-of-life and more batteries are retired from second-life applications, further reducing the need for additional extraction of critical materials. By using a 90% collection rate and recycling efficiency by 2030, the analysis assumes that many global regulations and end-of-life supply chains are developed.

Figure 15 shows the cumulative use of materials from passenger electric vehicles as a percentage of global reserves. The solid lines are the use of materials with recycling whereas the hashed lines are the use of materials without recycling. The hashed lines show how, without recycling, the cumulative use of cobalt as a percentage of known global reserves in 2020 increases from about 8% in 2030 to more than 20% by 2040 and 40% by 2050. The cumulative use of lithium and nickel as percentages of global reserves are similar and increase from about 3% in 2030 to about 15% in 2040 and about 30% in 2050. Cumulative use of graphite is about 5% of known global reserves by 2050, and manganese is less than 1%.

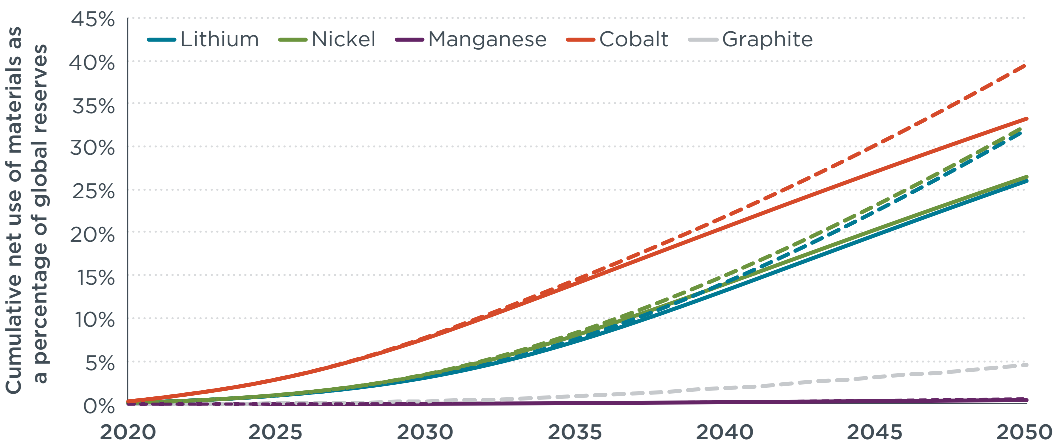

Figure 15. Cumulative use of cathode materials as a percentage of global known reserves as of 2020, with recycling (solid lines) and without recycling (hashed lines).

As shown in Figure 15, recycling reduces the cumulative net use of materials as a percentage of known global reserves. With the ramping up of global recycling facilities and the relatively efficient recovery of raw materials, recycling slows the need for additional extraction of materials. This is shown by the solid lines, where the cumulative use of materials as a percentage of global reserves begins to diverge from the hashed lines around 2035. With recycling, the cumulative use of cobalt as a percentage of global reserves is about 32% by 2050. The 2050 cumulative use of lithium and nickel is about 26% of known reserves as of 2020. Beyond 2050, as the raw materials needs with recycling are reduced compared to a no-recycling case, the cumulative use of materials as a percentage of global reserves could peak and approach a closed-loop battery supply chain. Recycling of graphite has been more limited due to its lower recovery value and global abundance and is thus not assessed here. Advancements in battery recycling technologies and changes in material prices could improve the value proposition of recycling graphite and reduce the need for additional mining.

Although it is considerably more speculative, an extension of this analysis beyond passenger electric vehicles to include other sectors helps provide a sense of scale for global material demand. After accounting for battery demands for other sectors from Figure 12 (i.e., consumer electronics, stationary storage, freight truck, and bus demand), the cumulative use of battery materials for lithium, nickel, and cobalt reach about 15% to 30% of proven global reserves by 2035, based on annual lithium-ion battery demand growing to about 4,700 GWh by 2035. Accounting for battery growth in other sectors approximately doubles the amount of materials needed. These developments underscore the need to develop global battery recycling capacity.

UNDERSTANDING ZEV SUPPLY SHIFTS

There are many uncertain aspects related to the preceding analysis for ZEV supply and material recycling in the next two decades. The supply trends depend on many long-term market and technology factors, including which battery chemistries become prevalent across major vehicle markets. In addition, automaker and battery supplier choices about battery chemistries in different proportions across major global markets impact supply trends. Such industry announcements and market trends that may impact the opportunities to mitigate the resource demands are examined.

Automaker decisions about battery chemistry greatly affect the need for materials. Initial automaker investments primarily focused on relationships with established battery suppliers in China (largely LFP), Japan (largely NCA), and South Korea (largely NMC). A shift to NMC chemistries with reduced cobalt content is becoming more common across industry announcements, and across markets. The NMC growth is driven by its ability to greatly increase specific energy and/or energy density and at the same time reduce materials supply cost. NMC-811 is primed to be the fastest growing chemistry: Its usage increased from 1% of the market in 2018 to 12% in early 2020 in China. NMC-811 is being deployed by automakers including BMW, General Motors, Nio, and Volkswagen, with suppliers including LG Chem and CATL (LeVine, 2020). The research literature indicates that there is the potential for increased specific energy density of 29% to more than 50% beyond NCM-811 with lithium- and manganese-rich cathode chemistries and silicon anodes (Schmuch et al., 2018; Li et al., 2020). This continued innovation beyond NMC-811 greatly reduces battery costs, while reducing overall material supply demand and producing options for automakers to hedge against supply constraints. At the same time, shifts in battery chemistry also affect the viability and economics of recycling, which is primarily driven by battery materials' market prices.

The long-term trend for LFP, common only in China, is more uncertain. Although LFP declined from being the dominant battery in China five years ago to about 13% of new electric vehicles in 2019, recent industry actions indicate LFP use could increase. After previously focusing on NCA in its U.S. production, Tesla introduced LFP and NMC batteries in its Shanghai-made Model 3 offerings in mid-2020 (Schmidt, 2020). Volkswagen has similarly indicated an openness to explore LFP in its China offerings (Reuters, 2019). LFP retains interest in China due its lower-cost batteries, lack of cobalt, safe battery pack architecture, continued LFP cell-to-pack improvements, and a higher acceptance for shorter-range BEVs for which LFP's lower density is less of a disadvantage (Lazuen, 2020). If LFP technology proves increasingly popular, raw material demands would be further reduced.

Industry-driven battery improvements aim to lower cost and extend electric vehicle range, but there are also policy drivers. Specifically, in China, a combination of two policies—vehicle purchase incentives and recycling requirements—reinforce an industry shift toward a more sustainable electric vehicle material supply. China's vehicle purchase incentives include minimum battery kWh-per-kilogram energy density criteria (Cui & He, 2020). This policy incentivizes battery technologies that not only offer cost and range improvements, but also use less battery materials per kWh. This policy has spurred China-based battery production of improved LFP and NMC-811 batteries, both of which reduce material demand. In addition, China's battery recycling requirement ensures that battery materials are recovered and reused, which spurs battery companies to design batteries they can later disassemble to extract the critical materials. With these policies in place through the market scale-up period of China's New Energy Vehicle regulation (Li, 2020; Cui, 2018), battery suppliers are pushed to embrace improved practices as they move to mass production.

DESIGNING POLICIES TO MAXIMIZE ZEV SUPPLY

High electric vehicle uptake markets typically have a comprehensive package of demand-side market development policies and supply-side industrial policies for battery and vehicle production. Fundamentally, the supply of ZEVs comes down to automaker investment decisions, which in turn rely on when companies commit to increasing ZEV production volume that they expect will best match future consumer demand and battery supplier commitments. As previously introduced, automakers at this early ZEV stage often have limited annual production of 10,000 to 40,000 electric vehicles that they supply to only a limited number of markets within a given continent. Low production volume inherently reduces the number of ZEV models available and pushes the few models to the few places with regulations and incentives. Several policies have emerged to help encourage automakers to more confidently invest in larger volume and in more ZEV assembly plants.

Table 4 summarizes policies designed to maximize ZEV supply, categorized by demand-side market development policies and supply-side industrial policies, and shows key examples of each. Demand-side market development policies include ZEV regulations, ZEV incentives and taxation, and infrastructure support. These policies spur consumer adoption by bringing more ZEV models across more consumer segments and in higher volumes, reducing the initial upfront cost barrier of ZEVs and ensuring an adequate charging infrastructure network. Based on global electric vehicle sales through 2019 and the automaker statements for future supply shown in Table 3, automakers tend to prioritize ZEV deployment in the markets where regulations, incentives, and infrastructure support policies are in place to overcome consumer barriers. Fiat Chrysler's 2018 financial report illustrates the company's compliance-focused global vehicle sales initiative, of which ZEV and CO_2 regulations are key drivers (Fiat Chrysler Automobiles, 2018). The fact that automakers are prioritizing ZEV supply in jurisdictions with regulations in place is further emphasized by Québec's ZEV standard compliance report that concludes "It is certain that the regulation is beneficial for Québec consumers since it encourages manufacturers to favor Québec over regions that do not maintain a similar system" (Québec Ministry of the Environment and the Fight Against Climate Change, 2020a).

Supply-side industrial policies include ZEV and battery manufacturing incentives, battery recycling requirements, and raw material mining incentives. Industrial policies complement market development policies and spur the electric vehicle, battery, and recycling industries to boost production scale to meet increasing demand. Substantial federal, regional, and local grants and tax incentives ranging from tens of millions to hundreds of millions of dollars have been issued to automakers to lower the barriers and costs of creating new electric vehicle and battery production facilities across China, Europe, and North America (Lutsey et al., 2018b).

Table 4. Policies to maximize ZEV supply

Category	Policy	Rationale	Program description	Example and reference
Demand-side market development	ZEV regulations	Bring more ZEV models across more segments and in greater volumes to market.	Require automakers to supply increasing quantities of ZEVs and provide clarity on increased long-term ZEV growth.	Québec ZEV standard "encourages manufacturers to favour Québec" over other regions (Québec Ministry of the Environment and the Fight Against Climate Change, 2020b)
	ZEV incentives and taxation	Help overcome the initial upfront cost barrier of ZEVs and motivate automakers to supply ZEVs.	Offer subsidies or tax incentives for ZEV purchases.	Norway's polluter-pay principle for vehicle taxation (Norsk elbilforenig, 2020)
	Infrastructure support	A full ecosystem of home, workplace, and public charging is key to market growth.	Direct deployment or financial support by electric power utilities, governments, and public-private partnership actions.	Netherlands infrastructure planning, funding, deployment, standardization, and partnerships (Netherlands Elektrisch 2020)
Supply-side industrial policy	ZEV manufacturing incentives	Support domestic ZEV manufacturing for greater supply and industrial competitiveness.	Grants, tax credits, subsidies, or loans for ZEV manufacturing.	Nissan UK plant £21 million UK grant and £197 million EU Investment Bank finance package (Nissan Insider, 2013).
	Battery manufacturing incentives	Support domestic battery manufacturing for greater supply and industrial competitiveness.	Grants, tax credits, subsidies, or loans for battery production.	Northvolt's Sweden battery gigafactory €52 million loan and $350 million in financing from the European Investment Bank (European Commission, 2020)
	Battery recycling requirements	Develop battery recycling capacity to reduce need for raw material mining and bolster supply.	Require and standardize recycling facilities for electric vehicle batteries, including material recovery rates.	China NEV battery recycling regulations set standards for facilities and raw material recovery rates (Ministry of Industry and Information Technology of the People's Republic of China, 2019)
	Raw material mining incentives	Support domestic mining to increase supply of critical materials for ZEV components.	Grants, tax credits, subsidies, or loans for raw material exploration and extraction.	$7.8 million to advance lithium extraction in California (California Energy Commission, 2020)

Industrial policies support much greater domestic ZEV production volumes and affect company decisions about where to construct facilities. This is demonstrated by the bidding war between Austin, Texas, and Tulsa, Oklahoma, to land Tesla's new billion-dollar U.S. assembly plant (Bellon & Shalal, 2020). Similarly, General Motors president Mark Reuss described the influence of Michigan's tax incentives on the company's $2.2 billion electric truck assembly investment as "a key element in making this investment possible…[and] helps ensure that Michigan will remain at the epicenter of the global automotive industry as we continue our journey to an electrified future" (General Motors, 2020). Because most electric vehicles are sold in the markets where they are produced, these policies have clear links with ZEV supply.

Several developments in Europe underscore the importance of industrial battery policies. The European Battery Alliance between key public and private stakeholders was formed in 2017 to advance the development of competitive battery manufacturing in Europe. The European Commission identifies the need for a strategic approach to batteries and recommends adopting an industrial battery strategy to maintain global industrial competitiveness in the automotive industry (European Commission, 2019).

The European Battery Alliance includes the European Commission and the European Investment Bank (EIB). These partnerships were critical to facilitating $350 million in financing support to Northvolt's new Sweden battery Gigafactory, supported from the European Fund for Strategic Investments. Northvolt cofounder and CEO Peter Carlsson described the strategic investment by saying, "The EIB has played a key role in making this project possible…Europe needs to build its own supply chain for large-scale battery manufacturing and the EIB is a true cornerstone of that process" (European Commission, 2020).

At the national level, the Netherlands' Strategic Approach to Batteries (Netherlands Central Government, 2020) is a good example of early steps governments can take to develop a battery strategy. The Netherlands' strategy provides recommended actions for five battery topics: origin of raw materials, collection and reuse, safety, economic value chain, and energy services. Example actions include financially contributing to key international due diligence initiatives, participating in cross-continent collaboration and cooperation, supporting revision of the EU Battery Directive, and stimulating battery research and development and innovation.

Adopting smart battery policies will be key to improving the sustainability and responsibility of the ZEV supply chain, including policies that address battery manufacturing, reuse, and recycling, as well as the sourcing of key materials. Examples include government funding for research and development into battery performance and use of alternative materials, incentives for battery cathode and anode manufacturing, battery eco-design or recycling requirements, recyclable material quotas for new battery production, incentives for raw material mining and refining, and mandating due diligence guidelines for responsible mining. Governments could also incentivize cross-industry collaboration to develop localized and closed-loop supply chains, such as the project in Europe between BMW, battery supplier Northvolt, and battery recycler Umicore that aims to create a sustainable closed-loop battery supply chain (Benchmark Mineral Intelligence, 2020)

The European Commission recommends the practices outlined in OECD's Due Diligence Guidance for Responsible Mineral Supply Chains (2016) (European Union, 2020). A 2019 blueprint by Transport & Environment identifies the key areas that potentially forthcoming battery regulations in Europe would ideally address, which broadly include more responsible material sourcing, use of renewable energy in battery manufacturing, and material recovery and recycling at end of life (Transport & Environment, 2019b). Governments that are considering adopting battery recycling regulatory measures would ideally focus primarily on the materials with highest value and that are associated with the greatest potential supply risk, including nickel, cobalt, lithium, and graphite.

Of the major markets, China has developed the most comprehensive and efficient ZEV support package by linking its market development policies to its industrial policies. China has the strongest system of consumer-focused market development policies through a combination of national and subnational consumer incentives, local registration incentives, and infrastructure deployment (Cui, et al., 2020). China's New Energy Vehicle regulation, restriction of incentives to vehicles with batteries manufactured in China, and joint-venture requirements provide assurance for domestic electric vehicle production. And China's electric vehicle and battery production incentives and recycling regulations that require and set standards for battery recycling facilities and recovery rates for critical materials ensure a growing supply chain. Together, this multipronged approach has accelerated development of China's ZEV supply chain and alleviates the likelihood of potential supply-side constraints. On a global scale, further developments of the battery recycling industry for critical materials is key to dramatically reducing use of raw materials and associated upstream supply chain concerns.

For markets grappling with ZEV supply constraints, governments can set a clear timetable that outlines the future development of stronger ZEV regulations. Extending regulatory requirements beyond single-digit market shares motivates automakers to invest in electric vehicles at sufficient volumes to be profitable within their core business and marketing strategies. Public government support for domestic electric vehicle and battery production spur industry to, at a minimum, retain a given country's share of the global automotive market—and potentially get in front of the global trend toward ZEVs. The major markets of China, Europe, and North America are volume drivers, and stronger regulatory requirements provide greater motivation for more companies to invest and deploy electric vehicles in greater volumes. Complementing these regulatory requirements with support for the industrial transition with new and converted vehicle, battery, and recycling plants will strengthen the local, regional, and global ZEV supply chain.

CONCLUSIONS

Although the transition to ZEVs is underway, many questions related to the supply of key materials, batteries, electric vehicles, and ZEV models across markets will need to be assessed over time. At the early stage of the transition in 2020, this report indicates that near-term ZEV supply dynamics can be analyzed based on public announcements from automakers and battery suppliers related to battery chemistry innovation, new and expanded battery plants, and vehicle assembly plans. Further, analyzing the volume of ZEVs and their underlying materials needed to meet long-term government ZEV transition goals puts the increasing battery material needs in broader context.

From this analysis, we draw the following five conclusions related to how technology, recycling, and policy can mitigate supply risks to the long-term transition to zero-emission vehicles.

Continued global efforts are needed to ensure that electric vehicle, battery, and material supply demands are met. This analysis indicates that electric vehicle and battery production can meet needs for government requirements and targets through 2025. Although battery production is tight in 2021–2022, the expanded battery cell and pack production already under development is well above the required near-term ZEV deployment from regulations around the world. What is less clear is whether the pace and scale of upstream raw material mining and refining into battery-grade quality is sufficient to keep pace with battery cell, pack, and vehicle manufacturing. The rush of capital into electric vehicles includes auto industry investments adding up to $180 billion in vehicle manufacturing, plus battery procurement investment of another $500 billion. This capital will need to flow upstream to unlock more mining and spur expanded refining capacity so that battery-grade materials are available to feed into battery cell production across Asia, Europe, and North America.

Raw material reserves are more than sufficient to support the global transition to ZEVs. Raw material needs for batteries for a transition to ZEVs will increase the annual need for cobalt, manganese, lithium, nickel, and graphite by 5 to 23 times from 2020 to 2035. Industry innovation and commercial developments toward increased battery specific energy and greatly reduced amounts of key materials (most prominently, at least 75% less cobalt per battery pack kilowatt-hour), will significantly reduce global material supply issues, even as ZEV deployment increases. Battery material needs for global passenger electric vehicles by 2035 reach 8% to 14% of proven global reserves for lithium, nickel, and cobalt. After accounting for battery demands for other sectors, battery material demand is approximately doubled.

A significant potential ZEV supply constraint is the supply of electric vehicle models to consumers. Despite the less-certain upstream developments to increase material mining and refining capability, the announced increase in electric vehicle and battery pack production volumes exceed annual global demand of 20 million electric vehicles sold and 1,100 gigawatt-hours of batteries supplied by 2025. This is more than sufficient to cover the world's regulatory requirements in China, Europe, and North America that have been adopted through 2020. However, because some states and countries have more aggressive 100% ZEV targets and are supporting those with higher levels of incentives, infrastructure, and consumer programs, there will be constraints from market to market (e.g., California in the United States, Québec and British Columbia in Canada, Norway and the United Kingdom in Europe).

Battery recycling practices will have a profound effect on long-term ZEV battery material supply. The analysis indicates that developing recycling streams to recover approximately 90% of the critical battery materials can significantly reduce the need for raw material mining from 2040 on. When accounting for second-life use of batteries after electric vehicle end-of-life, recycling can reduce the need for new material mining by 20% in 2040 and 40% in 2050. With recycling, the cumulative use of lithium and nickel could reach 25% of known global reserves by 2050, and 30% for cobalt. This is approximately a 25% reduction in the cumulative use of materials as a percentage of known global reserves in 2050 compared to a no-recycling case. Without recycling, cumulative use of these three key materials for global passenger electric vehicles could reach 30% to 40% of global proven reserves by 2050. Beyond 2050, as greater volumes of batteries become available for recycling, the need for new mining can be further reduced.

Comprehensive industrial-to-consumer policies are key to minimizing ZEV supply chain bottlenecks. Industry incentives, including for battery upstream raw material supply chain development, ensure key components reach higher volumes more quickly. Vehicle-level regulations for 2030–2040 requiring higher levels of electric vehicle production with sufficient lead time create certainty for industry investments and drive volume for more models to reach more markets. Demand-side support, such as incentives and infrastructure, provide near-term consumer support as technologies reach greater scale. Continued tracking of these supply chain steps is key to assessing where issues could emerge. Government actions can help bolster the financial viability of raw material extraction and refining to ensure battery-grade materials are sufficient to feed the projected demand. Cross-industry collaboration, public-private partnerships, transparency and traceability, and recycling regulatory and incentive measures are warranted to ensure batteries are designed for recyclability, collected upon end-of-use, and ultimately recycled. Government regulations for battery recycling would optimally focus primarily on the materials with the highest value and the greatest supply risk.

This study's scope, research, and analysis were broad. Ideally follow-on studies could be conducted that target specific upstream steps in the ZEV supply chain, including supplies in specific markets, specific existing policy context and future opportunities for specific policies and their design, and the relationship between raw material market prices and the pace and scale of investments across mining to recycling processes. Follow-on analyses could assess the opportunity and potential benefits of having the full electric vehicle, battery, and raw material value chain located within a major market or geopolitical area. As zero-emission truck technology and policy continue to develop, similar analyses to evaluate the associated long-term supply dynamics are warranted.

The implications of this research are wide-ranging. The barrier of ZEV model availability is applicable across most markets, and the need for battery cell production facilities and availability of high-quality battery-grade materials to keep pace with electric vehicle manufacturing is a global challenge. The policies assessed here can be adapted and implemented in markets of various sizes. This work shows the importance of governments simultaneously implementing policies to address demand- and supply-side issues to maximize the ZEV supply in their jurisdictions. The more governments work in concert worldwide, the greater the chance of mitigating supply chain risks and bolstering the global ZEV transition.

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APPENDIX

Table A1 summarizes the metal content in electric vehicle cathode materials (in kg/kWh) assumed in this analysis in 2020 and 2040. The table provides the relative content of the key metals in each battery cathode, including lithium, nickel, manganese, cobalt, aluminum, phosphorous, and iron. The metal content in next-generation lithium battery cathode chemistries is shown for 2040 and is an average of the seven next-generation chemistries assessed in this study: advanced LFP, high-voltage NMC and NCA, lithium-rich (LR) NMC, NMC-85, NCA-91, manganese-rich, and ultra-high nickel.

Table A1. Summary of metal content in electric vehicle battery cathodes assumed in this analysis in 2020 and 2040 (kg/kwh)

Year	Material	NMC-111	NMC-532	NMC-622	NMC-811	NCA	LFP	LMO	Next-gen
2020	Lithium	0.14	0.13	0.12	0.11	0.11	0.08	0.09	N/A
	Nickel	0.40	0.53	0.61	0.77	0.75	0	0	N/A
	Manganese	0.37	0.30	0.19	0.09	0	0	1.45	N/A
	Cobalt	0.40	0.21	0.20	0.10	0.14	0	0	N/A
	Aluminum	0	0	0	0	0.02	0	0	N/A
	Oxygen	0.65	0.58	0.55	0.52	0.51	0.74	0.85	N/A
	Phosphorous	0	0	0	0	0	0.36	0	N/A
	Iron	0	0	0	0	0	0.64	0	N/A
2040	Lithium	0.08	0.07	0.07	0.07	0.06	0.05	0.05	0.06
	Nickel	0.23	0.31	0.35	0.44	0.43	0	0	0.34
	Manganese	0.22	0.17	0.11	0.05	0	0	0.84	0.06
	Cobalt	0.23	0.12	0.12	0.06	0.05	0	0	0.03
	Aluminum	0	0	0	0	0.01	0	0	0.01
	Oxygen	0.38	0.34	0.32	0.30	0.29	0.43	0.49	0.23
	Phosphorous	0	0	0	0	0	0.21	0	0.03
	Iron	0	0	0	0	0	0.37	0	0.05

Note: numbers in table are rounded

Our analysis assumes cathode specific energy (watt-hours per kilogram) improvements of 1% per year through 2040. We also incorporate cell efficiency improvements from improvements in the anode and battery pack. We analyze a 15% anode improvement by 2030 (1.5% per year from 2020 to 2030) as well as a 20% cell to pack improvement by 2030 (2% per year from 2020 to 2030). These improvements are in line with several studies (Berckmans et al., 2017; Li et al., 2020; Lutsey & Nicholas, 2019; Schmuch et al., 2018) as well as corporate announcements from companies such as BASF, CATL, Tesla, and Panasonic.