Making the Most of Electric Vehicle Batteries

How Recycling, Innovation, and Efficiency Can Support a Sustainable Transportation Future

HIGHLIGHTS

Transitioning to electric vehicles (EVs) will slash air pollution and heat-trapping emissions and avoid the daily consumption of millions of gallons of gasoline in the United States. The nationwide transition is in its early stages and we have the opportunity to minimize the minerals needed for electrification and create a resilient, just, and sustainable EV supply chain.

UCS research quantifies the potential to minimize mineral demand for passenger cars and trucks in the United States through battery recycling, improved vehicle efficiency, right-sizing vehicle range for different driving needs, technological innovation, and increasing transportation options.

Key findings include:

- ***With smart policies, investments, and industry leadership, newly mined lithium needs can be reduced by nearly half (48 percent) from 2025 to 2050.***
- ***This reduction amounts to 1.5 million metric tons, equivalent to 180 million of today's typically sized EV batteries.***

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Introduction

Electrifying the US transportation system is essential to rapidly decarbonizing the economy and reducing the public health costs from tailpipe emissions. Electric Vehicles (EVs) powered by lithium-ion batteries have become the preferred alternative to gasoline vehicles. While EVs have not yet outpaced internal combustion engine vehicle sales, previous UCS analysis, along with many published studies, have shown these EVs vastly reduce global warming emissions and petroleum consumption (Pero, Delogu, and Pierini 2018; Reichmuth, Dunn, and Anair 2022). Transportation electrification holds the potential to all but eliminate the nearly 376 million gallons of oil burned every day in the United States as gasoline to power our cars and trucks (EIA 2024).

As the demand for batteries to power EVs increases with sales growth, so does the demand for the minerals needed to produce them. Mining these minerals—including lithium, nickel, cobalt, copper, and aluminum—carries social and environmental costs (Del Pero, Delogu, and Pierini 2018; RioFrancos et al. 2023). Minimizing the amount of minerals needed can avoid unnecessary mining and refining activities and their associated impacts while also continuing to support a rapid transition to electric mobility and a robust, resilient supply chain of battery-related minerals. This report quantifies the potential to minimize mineral demand for light-duty transportation[1] using several strategies, including battery recycling, improved vehicle efficiency, right-sizing vehicle range, technological innovation, and increasing mobility options. The results demonstrate that with smart policies, investments, and industry leadership, more than 1.5 million metric tons of mined materials could stay in the ground over the next two to three decades. By minimizing mining while electrifying and eventually relying mostly on recycled materials, we create a more resilient, just, and sustainable supply chain and energy future.

Why Demand for EV Batteries Matters

Electrified transportation is now a reality—EV sales have increased dramatically over the past decade due to increased popularity, EV incentives, and emissions regulations. This trend is expected to continue, resulting in global warming emissions reductions in the transportation sector that are needed to slow climate change (Clemmer et al. 2023). Yet, as more EVs hit the road, more minerals will be needed to produce them.

Lithium-ion batteries are used in EVs because of their high energy density, good performance, and long lifespan. There are several variations of the battery, but they all currently contain lithium, copper, graphite, aluminum, and steel, while other minerals used in the batteries vary and can include nickel, cobalt, manganese, iron, and silicon. EV battery production is only a part of the global demand for these minerals, but its demand increases as the transition to electric transportation intensifies. Lithium, nickel, and cobalt receive the most attention when EVs are discussed because of the unprecedented demand increase that vehicle electrification

[1] *The mineral forecast includes demand for lithium-ion battery minerals used in EVs and plug-in hybrids (PHEVs) for light-duty transportation as well as in transit buses.*

will create for them (Dunn et al. 2021; Liang, Kleijn, and van der Voet 2023). While there are sufficient mineral reserves, mining and refining capacity will need to grow to meet this future demand (Ambrose and Kendall 2020; Klimenko, Ratner, and Tereshin 2021; Shen, Slowik, and Beach 2024). Throughout this report, we will mostly focus on lithium because, other than aluminum and copper, it is the one material that cannot be substituted in lithium-ion batteries and it is illustrative of how mining for other battery minerals (for example, cobalt, nickel, and manganese) could be affected. It is also used primarily in batteries, so a rapid increase in battery demand translates into a rapid increase in lithium demand (Ambrose and Kendall 2020). Research has demonstrated that mining capacity, either proposed or in development, is expected to provide sufficient lithium to meet projected US EV mineral demand (Shen, Slowik, and Beach 2024). But reaching electrification goals without as many newly mined materials is a more resilient, just, and sustainable path to electrifying transportation.

How we design the batteries, the EVs, and the transportation system will significantly influence future battery, electricity, and mineral needs (RioFrancos et al. 2023). This presents an opportunity for policymakers and automotive companies to design a system that conserves minerals while electrifying. Using fewer materials to reach the same electrification targets can reduce the number of mines and mineral processors that need to be developed. This, in turn, reduces environmental and social costs and creates a more resilient future by decreasing reliance on the level of mine and mineral processing expansion required in business-as-usual forecasts.

Even if multiple demand reduction measures are taken, increased extraction will be needed to reach electrification goals (Shen, Slowik, and Beach 2024). While we know EVs reduce life-cycle global warming emissions and displace oil extraction and refining activities compared to their fossil fuel alternative, resource mining has harmed the health and well-being of communities around the world and disproportionately affected Indigenous Peoples (Owen et al. 2023). Therefore, crucial changes made to reduce potential harm to mining-affected communities and their environments are needed. Such changes include increased environmental regulations throughout mine development and the mining process, requirements for upholding Indigenous Peoples' sovereignty and human rights, and increased mineral tracing and auditing of mines. This report does not go into details of these impacts and solutions, but many resources provide additional information (Biden-Harris 2023; Earthworks 2024; UN 2007).

How Many Minerals Will Be Needed?

The total amount of batteries and associated mineral demand needed to electrify passenger transportation in the United States already is and will continue to be influenced by many factors. The batteries' design, the vehicles themselves, and the transportation system as a whole will significantly influence battery-related mineral needs in the future.

In this report, we explore EV efficiency and range trends of current EV models and sales and then calculate future mineral needs and the impact of varying the following:

- **Improved vehicle efficiency:** Making EVs more energy efficient can reduce the battery size needed while preserving a given vehicle range.
- **Right-sizing range:** In addition, matching vehicle range with drivers' needs can avoid overbuilding batteries, and access to reliable and convenient public vehicle charging can reduce range requirements.
- **Increased transportation choices, such as increased walking, biking, and transit use, and smarter land use planning:** By investing in safe and convenient sidewalks, bikeways, transit service, and the like, we can shift to more sustainable and economical transportation options, reducing the need for car ownership and related battery demand.
- **Innovation:** Advances that allow batteries to store energy using fewer materials decrease overall resource needs and battery costs.
- **Recycling:** Battery recycling can recover more than 90 percent of lithium, cobalt, and nickel (Yao et al. 2018), which can then be used to manufacture new batteries and offset the need for newly mined minerals.

This analysis presents three scenarios that illustrate the range of mineral demand requirements in different transportation electrification futures: a baseline mineral demand future, a future with low mineral demand, and a future with very low mineral demand.

Chapter 2: Reducing Mineral Demand while Electrifying Light-Duty Transportation

EVs have developed over the last decade, providing consumers with longer ranges and increased model choices. These increased options give consumers more opportunities to find the right EV for them. Additionally, researchers now have more data useful to assessing effects associated with changes in EV characteristics, such as range, efficiency, and battery capacity.[2] These factors affect battery sizes and, therefore, overall mineral needs. This section explores EV efficiency and range trends and the impact those trends could have on the transportation system's sustainability and resilience.

Improved EV Efficiency

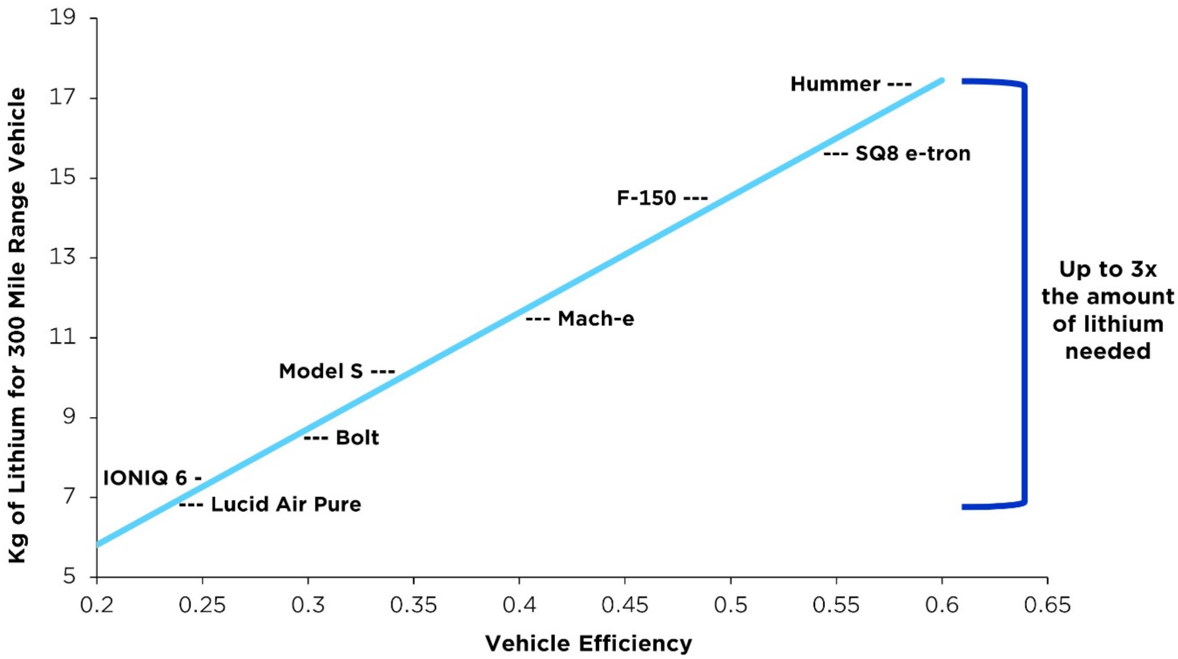
A more efficient EV needs less energy from its battery per mile. It can use a smaller battery and, therefore, requires fewer minerals to achieve a given range on a single charge. In addition, more efficient EVs can reduce overall electricity demand as they require less electricity to drive the same distance. A recent study found huge consumer energy cost savings associated with more efficient EVs due to the reduced need for investment in the electricity grid and charging infrastructure (EPRI-NRDC 2024).

In the transition to EVs, it is important to consider how vehicle trends, such as efficiency, will impact future mineral demand and how we can influence the market to achieve a more sustainable future. This study does just that.

An assessment of the EVs available in 2024 demonstrates that the most efficient EV currently available is the Lucid Air Pure, requiring 23 kilowatt-hours (kWh) per 100 miles, followed by the Hyundai IONIQ 6, requiring 24 kWh per 100 miles. The least efficient EV is the Hummer, which requires more than double those electricity needs, requiring 63 kWh per 100 miles, followed by the Audi SQ8 e-tron, requiring 54 kWh per 100 miles. Efficiency is impacted by many factors, including the weight, aerodynamics, onboard electronics' electricity draw, and energy loss in the drivetrain. Figure 1 demonstrates the impact efficiency has on battery pack lithium requirements.

[2] *This review of EV fleet characteristics uses data from the EPA (2024), and data on market share is from Atlas (2024).*

Figure 1. The Lithium Demand for EVs with a 300-Mile Range and Varying Energy Efficiencies (kWh per 100 Miles)



EVs' efficiency greatly influences mineral demand. For example, it takes over twice the amount of minerals for an F-150 to have a range similar to the Hyundai IONIQ 6's.
Note: Lithium demand is presented in kilograms (kg) using the NMC811 cathode, which contains nickel, manganese, and cobalt. Not all these batteries use this cathode, but NMC811 represents lithium needs similar to those of other chemistries, such as nickel-cobalt-aluminum (NCA), used in these vehicles. This data is taken from EPA (2024).

While EVs sold today are relatively efficient, two main trends could change that fact: (1) the influx of new EV models that are not as efficient, and (2) the declining prices of lithium-ion batteries (Shen, Slowik, and Beach 2024). In our analysis, we found that in 2023, the average EV sold in the United States was more efficient (31 kWh per 100 miles) than the average of available models (37 kWh per 100 miles).[3] This is because two efficient EVs dominated the market: the Tesla Model Y and Model 3 have consecutively represented over half of US EV sales. The Model Y's high sales share has kept the sales-weighted average of the light-duty truck classification[4] rated by the US Environmental Protection Agency (EPA) at a fairly efficient level. This likely will not be the case as other manufacturers continue to carve out more of the market and continue increasing the US sales-weighted average. Figure 2 demonstrates that the average EV model available is becoming less efficient over time.

[3] *In this report, we do not distinguish between efficiency improvements coming from a change in the mix of vehicles sold (i.e., shifting from larger to smaller EVs) and those coming from changes in electric powertrains.*
[4] *The EPA light-duty truck classification includes sport utility vehicles (SUVs), vans, and pickup trucks that either are heavier than 6,000 pounds or have other characteristics such as four-wheel drive (EPA 2023b; EPA 2024).*

Attention should also be paid to the currently small market slice of vehicles that are the least efficient but will likely result in a greater portion of future sales. The pickup truck model subclassification, listed in Table 1, has a sales-weighted average of 48 kWh per 100 miles. They first entered the market in 2023 and represented only 3 percent of sales. We assume this market share increases to match the gasoline market, in which pickups are about 16 percent of sales. If electric pickup truck efficiency does not improve, we will likely see their increased sales lead to a decrease in average EV efficiency. But, if we focus on improved efficiency for all EV types, including electric pickups, the mineral amount needed to electrify is reduced.

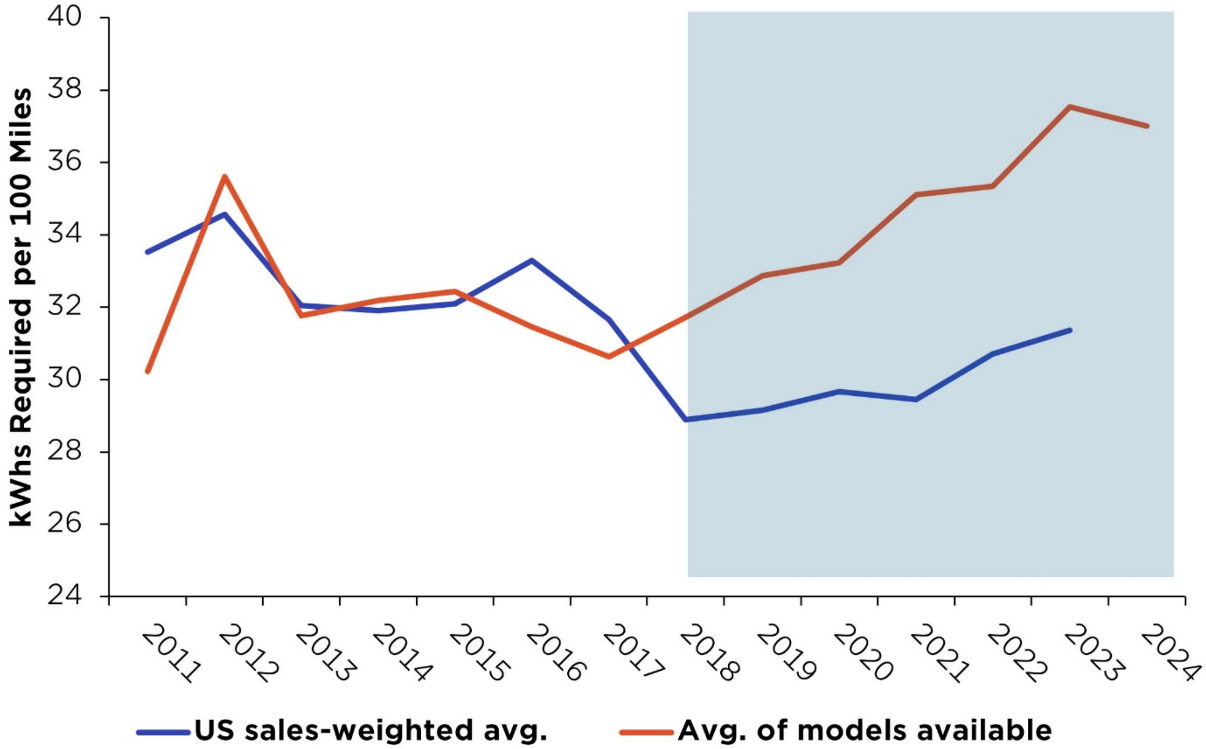
Table 1. Market Share and Sales-Weighted Efficiency of EV Cars and EV Light-Duty Trucks

EPA Classification	Sub-classifications of EVs	Top Selling Vehicle within the Category	US Sales-Weighted Efficiency in 2023	Market Share in 2023
Cars	All car variations[5]	Tesla Model 3	30 kWh per 100 miles	33%
	Station wagons (crossovers)[6]	Chevrolet Bolt EV	30 kWh per 100 miles	10%
Light-Duty Trucks	Pickup trucks[7]	Ford F-150	48 kWh per 100 miles	3%
	SUVs[8]	Tesla Model Y	32 kWh per 100 miles	54%

Early EV sales were mostly cars. However, as larger EVs have come to market, their sales shares are moving toward their gasoline vehicle equivalents' market sales shares. Increasing EV pickup sales in particular will likely mean lower overall average EV energy efficiency.

[5] *Includes two-seater, mini compact, compact, subcompact, midsize, and large cars classified by the EPA as cars.*
[6] *Includes station wagons and small and large crossover utilities classified by the EPA as cars.*
[7] *Includes small pickup, standard pickup, large pickup, large van, large utility, and large crossover utility classified by the EPA as trucks.*
[8] *SUV includes standard SUV, small SUV, small van, and small crossover utility classified by the EPA as trucks.*

Figure 2. The Average Efficiency of EVs in the United States



EV models entering the market trend toward being less efficient than current EVs. This is in line with the long-term trend of trucks and SUVs making up an increasing portion of total US passenger vehicle sales. For EVs, this began after 2017, when model year efficiency averaged 30 kWhs per 100 miles, and has continued to 2024, when the average efficiency of vehicles is 37 kWhs per 100 miles.
Note: The "Avg. of models available" line in this figure represents the average efficiency of all EV models available for sale each model year (not a sales-weighted average).

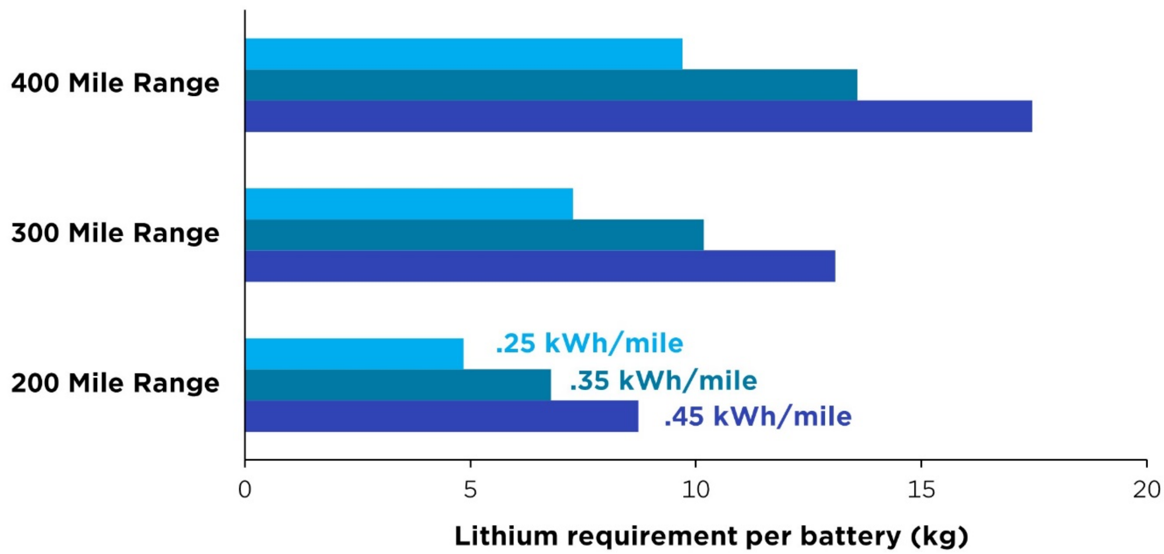
Right-Sizing Range

Vehicle range greatly influences battery size and the resulting mineral demand. EV range is the term for the number of miles an EV can go on a full charge. Range needs and preferences depend on commute length, terrain, weather, and the accessibility, availability, and speed of charging. The typical US driver drives 29 miles per day (FTS 2022), but consumers typically consider longer and more infrequent drives, such as road trips, when purchasing a car.

As publicly accessible charging infrastructure is built up around the United States and as public charging speeds increase, longer EV ranges will likely not be as frequently needed. This is beneficial to the sustainability and resiliency of our transportation system as well as to consumers—a smaller range in an efficient EV results in a smaller battery, therefore reducing the vehicle cost and the overall mineral needs to electrify.

EV efficiency becomes even more important as EV range increases. The longer an EV's range, the more important it is to make an EV efficient in order to keep battery sizes reasonable and mineral demand down. Figure 3 illustrates the difference in lithium required for a 200-, 300-, and 400-mile-range vehicle at three different efficiency levels. As shown, for a 400-mile-range EV with an efficiency rating of 24 kWh per 100 miles, the lithium required per battery is only slightly higher than that required for a 200-mile-range EV with an efficiency rating of 45 kWh per 100 miles.

Figure 3. EV Efficiency Becomes Even More Important as EV Range Increases



Efficiency counts: A 400-mile-range EV needing 24 kWh per 100 miles requires only slightly more lithium per battery than does a 200-mile-range EV needing 45 kWh per 100 miles. The average range and efficiency of EV vehicles sold impact overall mineral demand.
Note: These figures were calculated assuming an NMC811 battery with lithium requirements of 0.109 kg/kWh and a charging efficiency multiplier of 0.89.

As battery costs continue to decline, policy is needed to ensure efficiency is a priority. Manufacturers may choose to invest in vehicle efficiency improvements in order to achieve longer ranges while minimizing battery size and cost. But, if battery prices fall, we may see manufacturers choose to use larger batteries instead to achieve longer ranges unless they are required to prioritize efficiency.

Increasing Transportation Choices

Ultimately, demand for minerals used in EV batteries depends on the size of the batteries in individual vehicles (determined by the factors examined above) and the number of vehicles sold. Making it easier for households to meet their travel needs without using a private car for every trip could reduce overall demand for new vehicles and help meet climate targets.

With expected population growth and projected increases in vehicle use, US new vehicle sales are expected to grow (Clemmer et al. 2023; EIA 2023). Without significant improvements in mobility options, the US Department of Transportation (DOT) estimates that total light-duty vehicle miles traveled (VMT) will continue to grow by 0.3 percent to 0.8 percent per year through 2050 (FHA 2023), resulting in 2050 vehicle sales 8 percent higher than the DOT's 2024 estimate (EIA 2023).

High US dependency on personal vehicles is the direct result of intentional investments in highway networks throughout the 20th century, largely at the cost of low-income communities and communities of color/Black and Brown communities (Archer 2020) while withholding investments from other important aspects of a more complete transportation system, including buses, rail, and safe pedestrian and biking networks. This has resulted in the United States having less developed public transportation networks, less frequent service, more dangerous conditions for bikers and walkers, and more driving than peer countries (English 2018). If we invest in improving the convenience of transportation modes other than cars and in making key destinations closer or more convenient to get to, people have the option to take public transit, bike, or walk for more trips or reduce the distance they need to drive to reach the same types of places, therefore reducing their VMT. Many states are taking these steps for ambitious VMT reduction: California aims to reduce per capita VMT by 25 percent by 2035 and 30 percent by 2045 (California ARB 2022), Minnesota and Maryland aim to reduce per capita VMT by 20 percent by 2050 (Heggedal 2023; Maryland DOE 2023), and Washington State aims to reduce per capita VMT by 30 percent by 2035 and 50 percent by 2050 (Washington State Legislature 2024).[9]

When more travel options are available and frequent destinations are closer to home, households can meet their mobility needs with fewer cars. The number of vehicles owned per household varies per region, with state averages ranging from 1.2 to 4.5 vehicles per household (Moravec et al. 2024). These vehicle ownership rates can be influenced by both socioeconomic factors and the built environment, including development density, land use diversity, street design, distance to transit, and destination accessibility (Sabouri et al. 2021). When people need to use a car less because they can take more trips using alternative modes, they are more likely to forego a personal vehicle (Moody et al. 2021). They have the opportunity to downsize the number of vehicles in their household and forgo the cost burden of vehicle ownership (Silberg et al. 2020). Lowering the cost burden is important—the US Bureau of Transportation Statistics has found that low-income households spend 30 percent of their after-tax income on transportation (BTS 2024).

Innovation and Energy Density Improvements

Innovation has already played a huge role in reducing battery costs and the amount of minerals needed to produce an EV battery. Over the past 10 years, innovation in battery design, manufacturing, and composition has resulted in increased energy density, and fewer minerals are needed today to make an EV battery than in the past. Energy density describes the amount of energy that can be stored per kg of material—the higher the energy density, the less materials needed to store that energy. On average, a lithium-ion battery today is 25 percent more energy-dense than batteries made in 2015 (Walter et al. 2024).

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[99] *All of the VMT reduction goals use a 2019 baseline.*

This trend has been greatly beneficial, resulting in reducing battery costs and associated mining and manufacturing impacts (IEA 2024). If this innovation had not occurred, we would be in a very different place today. RMI, a US-based think tank, has estimated that if battery technology had remained constant at 2015 levels (i.e., excluding the chemistry changes, energy density improvements, second life use, and recycling gains made since 2015), we would have needed 58 percent more lithium, 127 percent more nickel, and 138 percent more cobalt in 2023 to produce the same supplied batteries (Walter et al. 2024). Previous forecasts have continually underestimated the advances that would occur, resulting in overestimates of current mineral needs (Walter et al. 2023).

Continued EV battery innovation and development is expected to improve battery energy density further and result in future batteries requiring fewer minerals. Historically, for every doubling in sales, energy density increased at an average of 6 percent, with the leading technology achieving 7 percent improvement per doubling. It is estimated that a third of this improvement is due to changes in chemistry over time, while the remainder (4 percent per doubling) is the estimated improvement for each given chemistry (Walter et al. 2024).

In addition, chemistries containing lower or even no cobalt are expected to represent a large portion of future sales, an assumption that would have been considered unachievable years ago (Walter et al. 2024). The energy density gains of lithium-iron-phosphate (LFP), a chemistry that does not contain nickel or cobalt, along with the decision of Tesla, Rivian, and Ford to offer vehicle models with this chemistry, has significantly changed the demand trajectory of nickel and cobalt, two minerals that were expected to be essential for mass-market EVs.

Recycling

When an EV retires, the battery can be reused, repurposed, and recycled. Minerals recovered from recycling can replace those newly mined and have significantly lower environmental impacts. By ensuring batteries are recycled using processes that have high rates of mineral recovery and also that the materials are then used to produce next-generation batteries, we can reduce battery supply chain emissions of carbon dioxide (Ciez and Whitacre 2017) and oxides of sulphur and nitrogen (Dunn, Kendall, and Slattery 2022).

Battery recycling processes have demonstrated at lab and industrial scales that upwards of 90 percent of lithium, cobalt, and nickel can be recovered and then used in the manufacture of new batteries (Yao et al. 2018). Recovery rates depend on the processes used; cobalt and nickel are recovered in all processes, but lithium recovery varies even when technologically possible, mainly because it is a lower-value mineral. To create a sustainable and circular process, it is essential that minerals are not lost or wasted. Thus, lithium should always be recovered at high rates, even when the lithium market price dips.

Considering the long car lifespan, there is not a substantial number of batteries currently retiring and, therefore, there is a shortage of recycled materials available. To electrify the transportation sector, newly mined minerals will be needed initially. This initial demand will vary based on transportation and battery characteristics, a focus of this report. As EVs reach 100 percent of vehicle sales in 2035, mineral demand flattens and battery retirements start to provide a greater source of secondary materials. This results in the declining need for newly mined minerals. The amount of demand able to be met with recycled content depends highly on mineral recovery rates (Dunn, Kendall, and Slattery 2022). The European Union (EU) has recently recognized the need for policy intervention to specify percent-recovery rate requirements in the recycling process and thereby ensure a recycled supply (EP&C 2023).

Prior to recycling, many batteries are expected to be suitable for reuse in an EV or repurposing after retiring from their first use. Battery reuse consists of reusing a battery in a vehicle, sometimes after refurbishing. Batteries can also be repurposed for a different application, such as stationary energy storage. Reuse and repurposing do prolong the battery's lifespan, which means it will not be available for recycling until a later date. While this lessens short-term recycled mineral availability, it also offsets the need for stationary or vehicle battery replacements, effectively reducing overall environmental impacts by displacing the need for the manufacture of a new battery (Dunn et al. 2023).

Chapter 3
The Path to a Sustainable EV Future

As described above, many factors will contribute to the future demand for minerals while we transition to EVs. We examine two scenarios that can reduce overall mineral demand while electrifying light-duty transportation and compare these to a baseline future (Table 2). In all these scenarios, we assume a rapid increase in EV sales, reaching 100 percent of new light-duty sales by 2035—consistent with UCS modeling demonstrating feasible pathways to midcentury decarbonization targets (Clemmer et al. 2023). The scenarios include mineral demand for both light-duty and transit EVs and PHEVs. We include transit in this light-duty analysis because we would like to assess the overall impact of increased transportation options on VMT and light-duty vehicle mineral demand. We also assume a high collection rate of old batteries (90 percent), a portion of which are repurposed (30 percent) and eventually recycled.

Table 2. Future Mineral Demand Scenarios and the Levers Assessed for Demand Reduction

	Baseline Scenario	Low Mineral Demand Scenario	Very Low Mineral Demand Scenario
Efficiency	2023 average for cars and trucks until 2050, but the truck market share increases	10% improvement by 2035 from 2023, held steady until 2050	20% improvement by 2035 from 2023, held steady until 2050
Average Range	Increased to 325 miles in 2035 and held constant to 2050	300 miles (same as 2023 average) and held constant to 2050	Decreased to 275 miles in 2035 and then held constant to 2050
Increased Energy Density	18% energy density increase from 2024 to 2050 (4% learning rate)	No change to baseline	22% energy density increase from 2024 to 2050 (5% learning rate)
Annual New Vehicle Sales	8% increase in light-duty vehicle sales from 2024 to 2050 consistent with 8% increase per capita VMT	4% decrease in light-duty vehicle sales from 2024 to 2050 consistent with 14% decrease per capita VMT	16% decrease in light-duty vehicle sales from 2024 to 2050 consistent with 35% decrease per capita VMT
Recycling: Lithium Recovery Rate	50% of lithium recovered for all years	50% of lithium recovered until 2030. 80% recovered from 2031 to 2050	90% of lithium recovered for all years
Description	EVs reach 100% of vehicle sales in 2035 and sales shares of EV cars and trucks follow similar trends to gasoline vehicles. EV batteries become more energy-dense, allowing for battery capacity and range to increase. Some lithium is recovered in the recycling processes.	Efficiency is prioritized and charging infrastructure is expanded, thereby reducing new vehicle battery size. Investment in increased mobility options and city planning reduces new vehicle sales. Policy is implemented to increase lithium recovery from recycling.	Additional measures are taken to increase efficiency and energy density and reduce range needs and new vehicle sales. The best available technology is used for recycling, resulting in high lithium recovery.

Early EV sales were mostly cars. However, as larger EVs have come to market, their sales shares are moving toward their gasoline vehicle equivalents' market sales shares. Increasing EV pickup sales in particular will likely mean lower overall average EV energy efficiency.

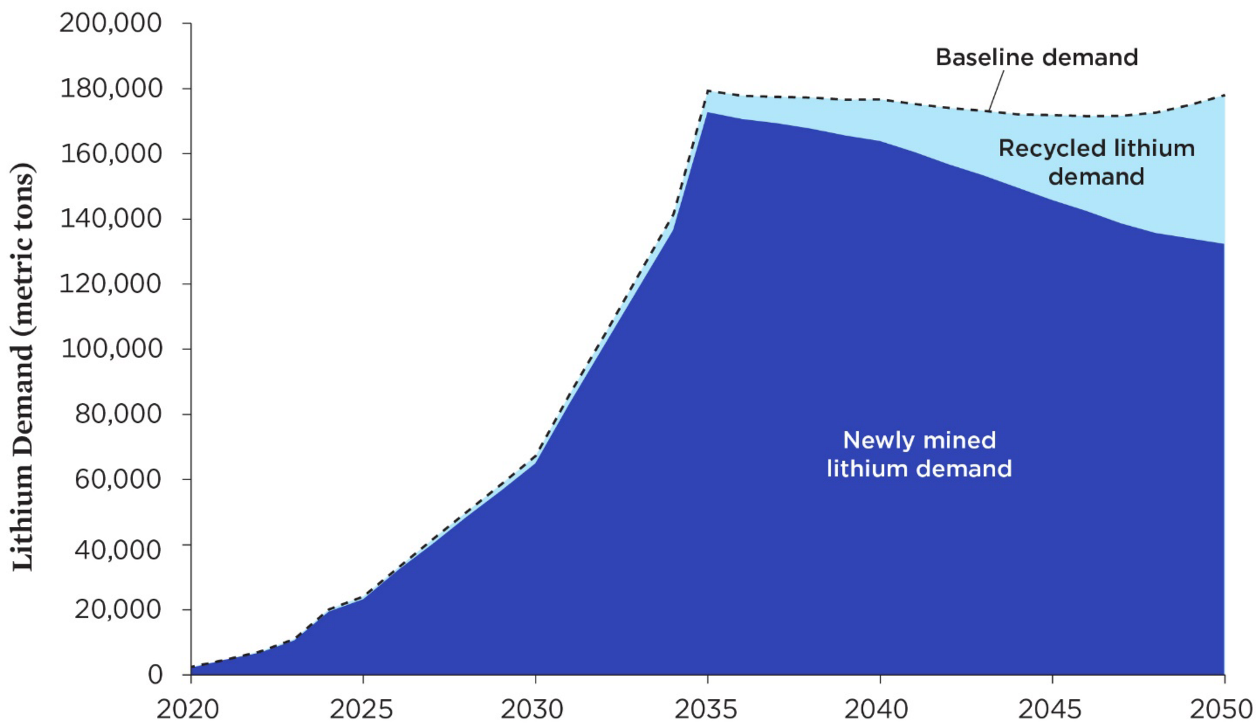
Baseline Scenario

In this scenario, EVs will continue to be the norm into the future, supported by the sustained deployment of publicly accessible EV chargers. The average range of vehicles sold continues to increase, reaching a 325-mile average by 2035. EV's efficiency remains similar to today; however, EVs, on average, become less efficient as electric trucks become a larger share of EV sales, matching that of current and projected gasoline vehicle sales fractions. The EPA-classified truck share grows from 55 percent to almost 70 percent of total light-duty EV sales beginning in 2030, equivalent to Annual Energy Outlook (AEO) estimates (EIA 2023). The truck classification includes both SUVs and pickup trucks, but pickup trucks notably also increase to align with current sales trends, going from 3 percent of total light-duty EV sales in 2023 to 16 percent from 2030 on. Overall, US annual new vehicle sales continue to grow, reaching 19 million per year, or 8 percent more than in 2024.

Lithium-ion batteries used in EVs continue to move toward lower cobalt chemistries, and energy density continues to improve at historical rates: 4 percent improvement every time cumulative kWh sales doubles (Walter et al. 2024). In this scenario, only some of the recycling processes recover lithium due to the volatile and relatively low price of lithium. Therefore, we assume 50 percent of lithium is recovered during the recycling process. While lower than technologically possible, this percentage is in line with the battery recycling requirements the EU imposed until 2030 (EP&C 2023), and the United States may not see lithium recovery reach desired rates unless requirements are set.

Results show that by 2035, battery mineral demand will level off as EVs reach 100 percent of new sales (see Figure 4). Lithium demand increases from about 24,000 metric tons per year in 2025 to about 180,000 metric tons annually in 2050 (about 130,000 metric tons newly mined). As demand flattens and batteries begin to retire, recycled materials can meet a greater share of mineral demand. However, while there is potential to offset a high amount of newly mined lithium needs, the low lithium recovery rate results in recycled content meeting only 26 percent of lithium demand in 2050.

Figure 4. Annual Lithium Demand for EV and PHEV Light-Duty Transportation and Transit Buses in a Baseline Scenario



In the Baseline scenario, lithium demand grows to 180,000 metric tons in 2035, when all vehicle sales are electric. Lithium recovery rates from recycling are assumed to be low due to lack of policy, leading to recycled materials meeting only about 26 percent of lithium demand in 2050.

Low Mineral Demand Scenario

In this scenario, advances in vehicle efficiency, expanded charging infrastructure, and slower increases in annual vehicle sales resulting from expanded access to non-car mobility options (transit, rail, walking, biking, etc.) and smarter land use policy lowers battery mineral demand.

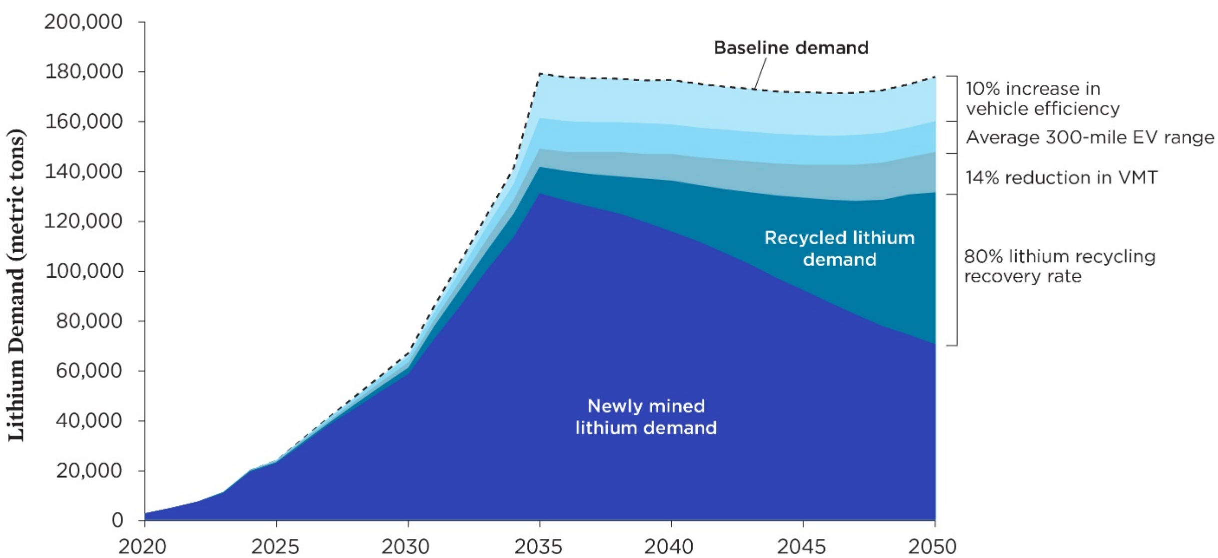
EV efficiency improves by 10 percent compared to today's levels, but the overall sales mix of cars and trucks remains similar to today's gasoline vehicles and that used in our Baseline scenario (30 percent cars and 70 percent trucks). Advances in battery charging technology and accessibility allow for average vehicle ranges of 300 miles, lower than in Baseline.

Investments allow households to become less car-dependent over time as a result of expanded transit and alternative mobility options and compact community design, which we have modeled to lead to fewer cars needed per household. By 2050, US annual new vehicle sales will slightly decline, reaching 17 million per year, or 4 percent fewer than projected 2024 sales.

The low mineral demand scenario results in a yearly lithium demand of about 130,000 metric tons in 2050, or a 27 percent decrease from that in the Baseline scenario. By 2035, mineral demand for batteries will level off as EVs reach 100 percent of new sales. By taking the steps outlined above, we see a cumulative reduction in newly mined lithium demand amounting to about 900,000 metric tons from 2025 to 2050, equivalent to about 110 million EV batteries.[10] Figure 5 demonstrates that efficiency gains and reduced average vehicle range result in the largest savings of overall lithium demand.

The lithium recovery rates from recycling increase in this scenario, meeting the EU requirements of an 80 percent average lithium recycling recovery rate in 2031. This drastically decreases the amount of newly mined lithium needed. Recycled content can then meet 47 percent of demand in 2050.

Figure 5. Annual Lithium Demand for EV and PHEV Light-Duty Transportation and Transit Buses with Moderate Reduction Strategies Implemented



Implementing strategies that result in better EV efficiency, shorter-range vehicles, and reduced VMT will cause a 27 percent decrease in lithium demand in 2050. Additionally, 47 percent of 2050 lithium demand can be met by recycled content.

Very Low Demand Scenario

In this scenario, vehicle energy efficiency is prioritized and there is a 20 percent efficiency gain in comparison to the Baseline scenario as a result of focused efforts. The 20 percent gain results in an average of 28 kWh per 100 miles for new EVs from 2035 to 2050. This total average includes the average electric car reaching 24 kWh per 100 miles, comparable to the Hyundai IONIQ 6, one of the most efficient models available today. Battery advancement

[10] *Assuming an 80 kWh battery with lithium content of 0.102 kg/kWh.*

continues, with energy density increasing slightly faster than historical averages, but similar to the rate of density gains by the most efficient batteries on the market (Walter et al. 2024). The increased effort to gain efficiency and energy density is focused on making EVs more affordable rather than on extending range with larger batteries. In addition, ubiquitous, convenient, and fast public charging allows drivers to choose more affordable, lower-range vehicles that meet their needs. An average range of 275 miles is used in this scenario, slightly higher than the 2023 Chevrolet Bolt. We chose a 275-mile average because it would more than cover most drivers' daily needs while also allowing them to go for over three hours on the occasional road trip without stopping.

The increased ease of using alternative modes of transportation results in a 35 percent reduction in VMT and overall car ownership (note that this is less than the Washington State VMT reduction goal). By 2050, US annual new vehicle sales will slow and slightly decline in comparison to Baseline, reaching 15 million per year, or 5 percent less than 2023 annual sales.

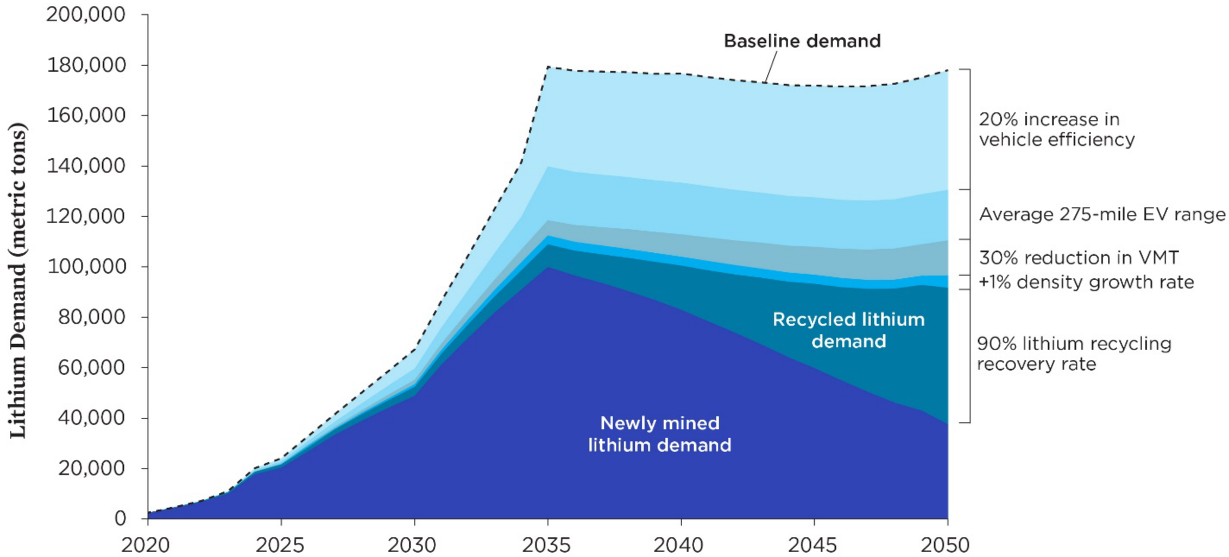
In this scenario, projected lithium demand in 2050 is 48 percent less than in the Baseline scenario. Demand for newly mined lithium in 2050 is 71 percent less due to the overall demand reduction and higher amounts of lithium recovered during the recycling process. Batteries are recycled using the best available technology, resulting in 90 percent of the lithium being recovered. In 2050, 59 percent of lithium demand can be met with recycled content, compared to 26 percent in the Baseline scenario. Cumulatively, this scenario reduces newly mined lithium needs by 1.5 million metric tons from 2025 to 2050, the equivalent of about 180 million EV batteries.[11]

Figure 6 demonstrates that the impact of each demand-reducing strategy has grown in comparison to the Low Mineral Demand scenario represented in Figure 5, with energy efficiency gains and recycling specifically cutting a large amount of overall lithium demand. We have found that reducing the mineral needs to electrify leads to both a higher percentage of demand that can be met with recycled minerals and an overall lower demand for newly mined minerals in the long term. Figure 7 shows that in the Baseline scenario, in which the average EV battery size remains unchecked and lithium recovery rates are low, the ability to reach high recycled content rates gets pushed out to later years.

Additionally, if the demand reduction strategies are implemented on their own, we still see a decrease in overall mineral demand. Table 3 demonstrates that the greatest impact on lithium demand from 2025 to 2050, a total of 22 percent less lithium needed, is due to increasing EV efficiency by 20 percent.

[11] *Assuming an 80 kWh battery with lithium content of 0.102 kg/kWh.*

Figure 6. Yearly Lithium Demand for EV and PHEV Light-Duty Transportation and Transit with Ambitious Reduction Strategies Implemented



Implementing strategies that result in better EV efficiency, right-sized range, and reduced VMT will result in savings of 1.5 million metric tons of newly mined lithium from 2025 to 2050. Due to reduced demand and a higher lithium recovery rate, more demand can be met by recycled content, totaling nearly 60 percent in 2050.

Table 3. Lithium Demand Reductions Resulting from Implementing One Reduction Strategy

Scenario	Cumulative Demand 2025–2050 (metric tons)	Percent decrease from Baseline Scenario
Baseline	3,534,870	
20% Efficiency Gain	2,751,536	22%
275 Mile Range	2,818,099	20%
35% Reduction VMT	3,003,068	15%
+1% increase in energy density	3,146,677	11%

Increasing EV efficiency by 20 percent will lead to the highest reduction—22%—of overall mineral needs from 2020 to 2050. The next highest reduction—20%—results from reducing EV range to 275 miles.

Reduction Strategies Also Influence Nickel and Cobalt

The value of implementing these mineral demand–reducing strategies while electrifying extends beyond lithium to the other minerals in the battery pack (e.g., cobalt, nickel, graphite, aluminum, steel, and iron). Figure 7 shows that these strategies would reduce battery demand for cobalt and nickel by nearly 40 percent from 2020 to 2050.

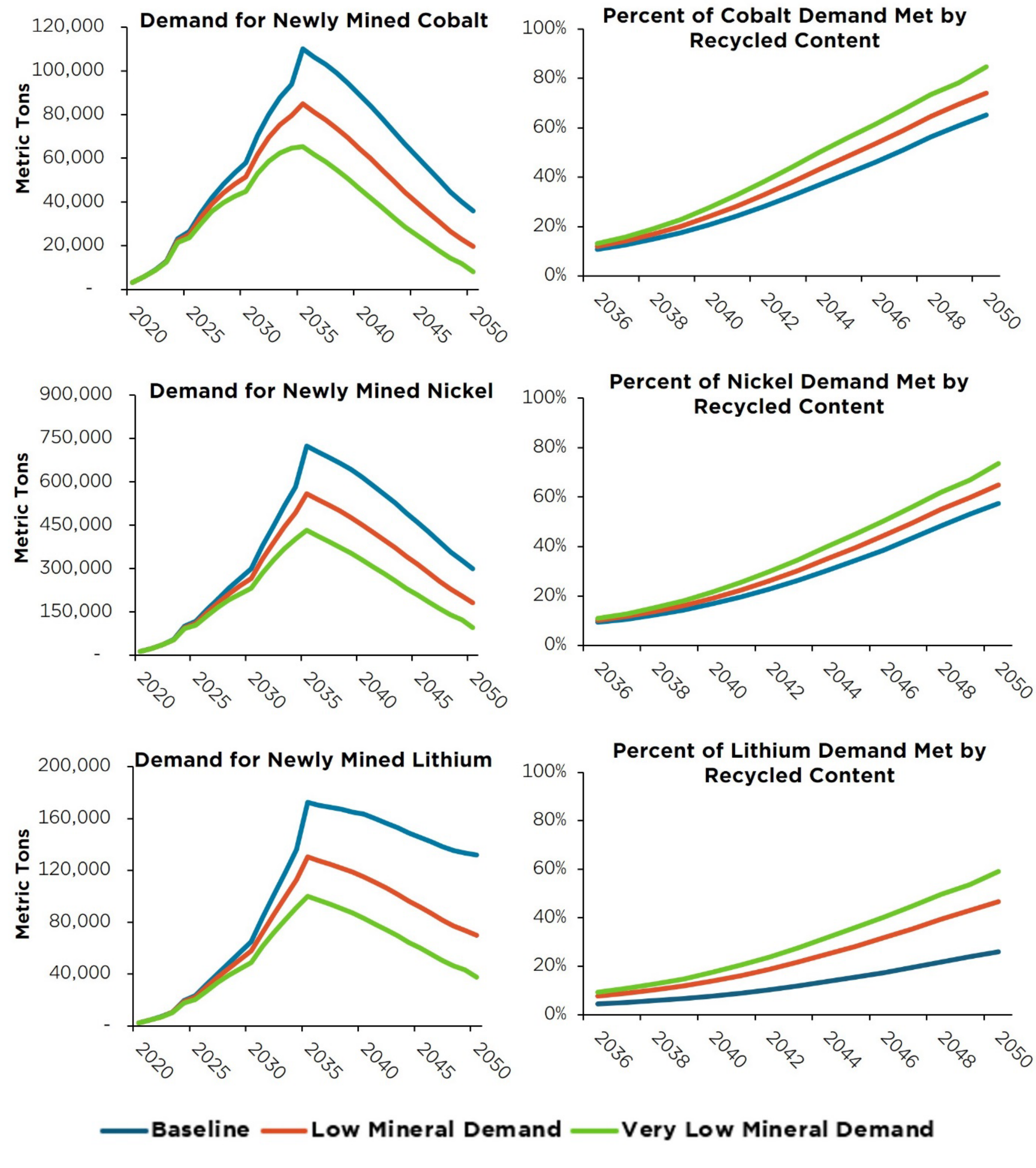
In addition, the continued trend of changing minerals within the lithium-ion battery cathode (also known as the battery's positive electrode) has resulted in even more cobalt and nickel needs being met with recycled content than demonstrated for lithium.[12] There are two trends responsible: (1) the continued push to develop a cathode that does not contain any nickel or cobalt and instead contains iron-phosphate (LFP), and (2) the push to develop chemistries made up of less cobalt and more nickel.

[12] Note that the changing cathode chemistries do not have a large impact on lithium because the chemistries have similar lithium content.

We forecast that by 2050, about 35 percent of future cathodes will be LFP and the remaining 65 percent will use low cobalt and high nickel chemistries. This material substitution is beneficial because LFP technologies have lower emissions (Ambrose and Kendall 2016) and social impacts associated with their mining and manufacturing (Murdock, Toghill, and Tapia-Ruiz 2021). Because lithium-ion batteries are a driving force behind the increased need for cobalt and class I (high purity) nickel, the lessening of future demand could slow future mine expansion needs and create a more resilient and lower-impact transportation system.

Lithium-ion battery recycling consistently recovers nickel and cobalt due to their high value, meaning that even in our Baseline scenario more recycled nickel and cobalt will be available. However, these cathode chemistry changes that will likely occur over the next several decades influence all our scenarios and result in more cobalt demand able to be met with recycled content than was found for nickel and lithium. In 2050, about 65 percent of cobalt demand can be met with recycled content in the Baseline scenario, while 85 percent can be met in the Very Low Demand scenario. The demand for newly mined nickel also drops substantially in the two scenarios from 2035 to 2050, but not as fast as demand for newly mined cobalt: about 60 to 75 percent of nickel demand is able to be met with recycled content, depending on the scenario.

Figure 7. Reduction Strategies’ Potential Effect on Newly Mined Cobalt, Nickel, and Lithium Demand



Reduction strategies can be taken to greatly reduce demand for newly mined lithium, cobalt, and nickel while electrifying passenger transportation. In 2050, we can meet 59 percent of lithium, 74 percent of nickel, and 85 percent of cobalt demand with recycled minerals by implementing ambitious demand reduction strategies while electrifying.

Chapter 4
Policy Recommendations for the Efficient Use of Minerals

Electrifying our transportation system will reduce climate-changing emissions and air pollutants. But how we get to fully electric matters. By minimizing the amount of overall electricity and newly mined minerals needed to decarbonize, we can drastically decrease impacts and make an even more sustainable system. Doing so will require a systems-wide strategy, including sustainability-driven EV product development, transportation planning, and required EV battery recycling. Urged on by policies aimed at incentivizing EV efficiency, recycling/use of recycled materials, advancing battery innovation, and increasing charging availability, automakers can deliver EVs that meet drivers' needs without unnecessarily increasing mineral demand. As part of this strategy, we recommend the following actions.

Vehicle Standards Aimed at Incentivizing Increased EV Efficiency

Vehicle standards have proven to be an effective tool for increasing efficiency and decreasing passenger vehicle emissions in the United States. We measure gasoline vehicle efficiency by the miles that can be traveled on one gallon of gasoline (MPG). MPG requirements set by the National Highway Transportation Standards Administration (NHTSA) have helped drive efficiency increases in the US fleet average from 13 MPG in 1970 to 35 MPG in 2023 (EPA 2023b). Limitations imposed by Congress on consideration of alternative fuels such as electricity limit the ability for NHTSA's fuel economy regulations to drive efficiency gains for EVs, but it is clear that regulation can be a successful driver of efficiency.

Passenger vehicle global warming emissions are also regulated. The Clean Air Act gives the EPA authority to limit emissions from the transportation sector. The stringency of these requirements has been successful in pushing automakers toward developing and investing in the development and manufacture of EVs. Currently, these standards cover only tailpipe emissions, and, therefore, they consider EVs to be zero-emission vehicles (EPA 2023a). If these standards consider the emissions associated with the electricity used to charge EVs and the upstream emissions of producing gasoline for gasoline vehicles, there is also potential for these standards to be used to promote EV efficiency (Huether 2024). If emissions from the electricity grid were assigned to EVs, more efficient EVs would be shown to be responsible for lower upstream emissions rates due to using less energy per mile.

Absent regulatory standards for EV efficiency, there is a risk that EVs could become less efficient over time, as noted in our Baseline scenario. Currently, battery costs are a significant portion of an EV's overall cost. In order to make longer-range EVs affordable, automakers are currently motivated to make their vehicles efficient to minimize battery size. However, even in today's market with relatively high battery costs, there is a wide range of EV efficiency between models, as demonstrated in Figure 1. As battery prices fall in the future, as is predicted, the price signal for manufacturers could become less effective in encouraging overall vehicle efficiency. Fuel economy and global warming standards have proven essential to reduce emissions and lower fuel consumption from the nation's gasoline automobiles. Similar policies for EVs may prove to be just as important.

Increased Deployment of Charging Infrastructure

Although the vast majority of EV charging happens at home or work, reliable, fast, and easily accessible public charging can enable a higher prevalence of lower-range vehicles by helping decrease the maximum range drivers feel they need. A vehicle's range influences its battery size. Therefore, a lower-range and efficient vehicle could provide lower-cost EV options while reducing the amount of minerals needed. Continued investment in public charging infrastructure outside of home and apartment charging could help lower "range anxiety," resulting in more consumers opting to purchase lower-range vehicles.

Public charging infrastructure can be expanded by making tax credits and incentives available and also by direct investments in charging equipment, grid infrastructure, and distributed energy resources (such as on-site solar or batteries) to support charging energy demands. In addition, policies written to ensure charger reliability and payment method accessibility are important for increasing access to public charging.

Increased Investment in Rail and Transit Infrastructure

The United States has a long history of prioritizing highway investments over infrastructure that creates safe and accessible alternative modes such as public transit, biking, or walking. Highways were built through communities, mostly Black and Brown communities, displacing people's homes and businesses and leaving them with economic disinvestment and toxic air pollution. Investing in convenient and affordable transportation alternatives, along with more convenient community planning, can lead households to rely on fewer personal vehicles. For a clean, equitable, and multimodal transportation system, we must take the following actions:

- **Greatly expand transportation options.** We need a transportation system that offers abundant access to everywhere we need to go and that promotes economically thriving communities in both urban and rural areas. This means investing in networks of safe sidewalks and paths for micromobility options, such as bikes and scooters, and in public transportation that runs frequently and is wide-ranging, affordable, and clean.

- **Make transportation decisions through an equity and climate lens.** The costs and benefits of transportation investment decisions throughout society should be considered during decisionmaking processes. This means assessing whether transportation plans help achieve climate goals, reduce harm to impacted communities, and increase access and mobility for those who most need them. To achieve this end, state transportation departments need to be transparent and accountable for how they make decisions and allocate funds.

- **Make decisionmaking in transportation and land use planning more democratic, accessible, and equitable.** Many of the people who might benefit most from improved transportation options (including young people, people with disabilities, people of color, and lower-income people) are systematically underrepresented in transportation decisionmaking processes. These processes should be representative of the populations they serve and meaningfully engage communities most impacted by projects. Effective engagement will result in transit systems and pedestrian networks that better meet community needs and thereby reduce car dependence and resulting mineral demand in an equitable way (Shen, Higashide, and Cooke 2024).

Federal EV Battery Recycling Requirements

Minerals recovered from recycling old EV batteries can substantially reduce the need for newly mined materials and the impacts associated with mineral processing. In order to guarantee these batteries are recycled, a strong policy requiring recycling, reuse, and repurposing should be implemented. The EU in 2023 did just that, passing a strong extended producer responsibility policy that includes various other sustainability requirements such as required recycled content, mineral recovery rates, and battery data transparency (EP&C 2023). At the federal level, the United States has not yet taken action, but states have started to regulate recycling on their own. New Jersey passed the first-ever US requirement for end-of-life battery recycling, although it was not as comprehensive as the EU's policy (Electric and Hybrid Vehicle Battery Management Act 2024). California has been working on a stronger bill that includes extended producer responsibility, reporting, and a qualified recycler definition. In addition, other states are just now beginning to explore EV battery recycling policies. At the time of this publication, this includes Hawaii, Nevada, and Washington State.

Guiding principles that should drive battery recycling policy include the following:

- **The vehicle producer should be responsible for ensuring EV batteries are reused, repurposed, and eventually recycled.** Holding a centralized party responsible for ensuring these batteries are responsibly recycled helps regulators monitor and enforce the requirement. The automakers are best suited for this because they are a relatively small number of companies that have control over the design of the product. Extended producer responsibility does not necessarily mean producers have to handle the batteries themselves; rather, they would be responsible for making up cost differences. If they are responsible for costs associated with reuse or recycling, they are naturally incentivized to design these batteries for more efficient disassembly and recycling.

- **The battery recycling process should minimize environmental impacts and have a high rate of material recovery, especially for lithium, nickel, and cobalt**. How batteries are recycled matters. In order to replace newly mined minerals, the process needs to recover a high amount of battery-grade materials. Recycling processes have been proven to have the capability of recovering upwards of 90 percent of lithium, cobalt, and nickel (Yao et al. 2018). This report demonstrates the benefits of high recovery rates: using best available recovery technology results in meeting 60 percent of lithium demand with recycled material in 2050, compared to lower rates in the Baseline scenario, which result in only 25 percent of demand being met with recycled materials in 2050. In addition, recycling processes have varying environmental impacts, and high-heat processes that produce off-gasses and have higher global warming emissions should be avoided. Processes that recover the full cathode are in development and could be a lower-impact alternative (Gaines et al. 2021).

- **Prior to recycling, a battery should be reused, refurbished, and/or repurposed if it is safe and has remaining capacity.** By reusing and repurposing batteries, we offset the need to manufacture new batteries to serve that purpose and, therefore, reduce the associated life cycle emissions (Dunn et al. 2023). Many of the EVs retired have batteries with 70 to 80 percent of their battery capacity left. State of health and safety tests can determine whether they are viable candidates for reuse in a used vehicle or repurpose for use in stationary storage. Accessing information about the battery's health is not easy in the United States. To facilitate more efficient reuse and repurposing, information about batteries' health over time should be standardized and accessible when each battery is in a vehicle and after its removal. While the United States has not yet required this, the EU has mandated the collecting and sharing of this data to repurposers through a battery passport.

Improved Mining Standards, Mineral Tracing, and Transparency

Extractive processes such as oil drilling and mineral mining create adverse social and environmental impacts around the world. Current practices do not uphold the environmental and social standards that we expect of a sustainable economy. As we transition to electric transportation, we must consider routes for reducing mining's upstream impacts.

Researchers, advocates, and the EPA have demonstrated that US regulations are not strong enough to protect local communities from mining impacts (Biden-Harris 2023; Earthworks 2024; GAO 2005). Mining-affected communities are disproportionately Indigenous; in the United States, the majority of nickel, copper, lithium, and cobalt reserves and resources are within 35 miles of a Native American reservation (Block 2021), but these communities are not provided the United Nations right of Free, Prior, and Informed Consent. Advocates and the Biden-Harris Interagency Working Group on Mining Laws outlined research-backed arguments that the current mine development process does not support adequate local community engagement and that the 1872 Mining Law should be updated to provide proper incentives, prioritizations, and rights that will decrease associated impacts, especially those affecting Indigenous Peoples (Biden-Harris 2023).

Impacts from mining for materials that power US EVs go beyond just the boundaries of the United States. It is essential to implement mineral supply chain tracing and mine auditing to (1) hold companies responsible for sourcing from mines using unethical practices, and (2) incentivize EV manufacturers and mining companies to be better actors. The EU has implemented some requirements for mineral sourcing, including Organization for Economic Co-operation and Development Due Diligence Guidance and the use of a battery passport as a repository system (EP&C 2023). The United States should consider similar implementation and further support better mining practices by instituting transparent auditing through reputable organizations such as the Initiative for Responsible Mining Assurance. The United States has introduced legislation in Congress (the Critical Material TRACE Act of 2024) that partially addresses this issue by encouraging manufacturers to have a digital identifier on each battery that documents mineral origins and information on battery reuse, repurposing, and recycling.

Appendix A: Methodology

Material flow analysis is used to determine the minerals needed to electrify the light-duty transportation sector and the transit buses as the United States decarbonizes. This analysis assesses the impact of light-duty energy efficiency, range, battery size, innovation, and recycling on mineral needs. In addition, we assess how increased public transit and rail will affect car sales and, therefore, impact mineral demand. We begin by taking the model used in Dunn et al. (2024) and then modify to meet the needs of this analysis, which includes changes to EV efficiency, range, sales, and survival rates and the addition of transit bus parameters.

A.1. Light-Duty Vehicle Characteristics

To determine the mineral needs of EV batteries, we considered vehicle and battery characteristics, including vehicle type, EV efficiency, EV range, battery chemistry, and battery energy density improvements.

The battery capacity (kWh) varies depending on vehicle range (miles) and EV energy efficiency (kWh per 100 miles) trends. The range and energy efficiency are used for historical sales, and then the forecasted averages are varied based on analyzing historical trends (Atlas 2024; EPA 2024). For each scenario, we separated efficiency by EPA-rated cars and trucks, with the trucks split by pickup truck and SUVs. In 2023, the sales-weighted average efficiency of EVs was 31 kWh per 100 miles, with cars representing 45 percent of sales and trucks 55 percent (the truck classification includes pickup trucks, which represented 3 percent of sales). Over time, the US sales-weighted efficiency for all scenarios changes based on the car-to-truck ratio reaching the US norm of 30 percent EPA-classified cars and 70 percent EPA-classified trucks (pickup trucks represent 16 percent) in 2030 and continuing to 2050.

The efficiency for each of the two non-Baseline scenarios used assumes efficiency gains. The Low Mineral Demand scenario assumes a 10 percent efficiency gain compared to the Baseline scenario, equating to an average US-sales efficiency of 30 kWh per 100 miles. The Very Low Mineral Demand scenario assumes a 20 percent efficiency gain compared to the Baseline scenario, equating to an average US-sales efficiency of 27 kWh per 100 miles. The efficiency changes used do not rely on changing the car to truck ratio (vehicle down-sizing), but we did find that the 20 percent improvement in efficiency (26.87 kwh per 100 miles average) is slightly more efficient than a 15 percent efficiency improvement and 50/50 car to truck sales (27.71 kWh per 100 miles average). This indicates that the average fleet-wide efficiency improvement represented in this study could be achieved through a mix of technology improvement and right-sizing both range and vehicle type. The efficiencies used for each scenario are in Table A.1.

We did not capture changes to PHEVs in our scenarios. They are modeled separately with the US-sales weight average battery capacity for PHEV light-duty trucks and cars in Table A.3 and calculated from historical sales data (S&P 2024). Linear regression was used to forecast battery capacity (kWh) to 2035, when PHEVs are phased out.

Table A.1. Efficiency Used in Each Scenario, Broken Down by EPA Classification for Cars and Trucks

EPA Classification	Grouping Used in This Analysis	EPA Subclassification Grouped	Baseline Energy Efficiency in 2035 (2023 Sales Weighted Avg)	10% Gain from Baseline	20% Gain from Baseline
Cars	Cars	Two seater	30 kWh / 100 miles	27 kWh / 100 miles	24 kWh / 100 miles
		Minicompact			
		Compact			
		Subcompact			
		Midsize			
		Large			
		Small crossover utility			
		Large crossover utility			
Light Trucks	Pickup trucks	Small pickup	48 kWh / 100 miles	44 kWh / 100 miles	39 kWh / 100 miles
		Large pickup			
		Large van			
		Large SUV			
		Large crossover utility			
	SUV	Small van	32 kWh / 100 miles	28 kWh / 100 miles	25 kWh / 100 miles
		Small crossover utility			
		Small SUV			
2035 Average			34 kWh / 100 miles	30 kWh / 100 miles	27 kWh / 100 miles

The EPA truck classification is broken into two categories, pickup trucks and SUVs, due to the large variance between the efficiency of models within these two truck subclassifications.

Table A.2. Average Efficiency, Range, and Battery Capacity (kWh) Used in Each Scenario for 2035 to 2050

		Car		Truck	
Scenario	BEV Range (mile) 2035 to 2050	Energy Efficiency (kWh / 100 miles) 2035 to 2050	Battery Capacity (kWh) 2035 to 2050	Energy Efficiency (kWh / 100 miles) 2035 to 2050	Battery Capacity (kWh) 2035 to 2050
Baseline	325	30	87	36	104
Low Mineral Demand	300	27	72	32	85
Very Low Mineral Demand	275	24	59	30	73

Car and truck battery capacity (kWh) is calculated by multiplying the range by efficiency and a wall-to-battery energy loss multiplier of .89. (Dunn et al. 2024).

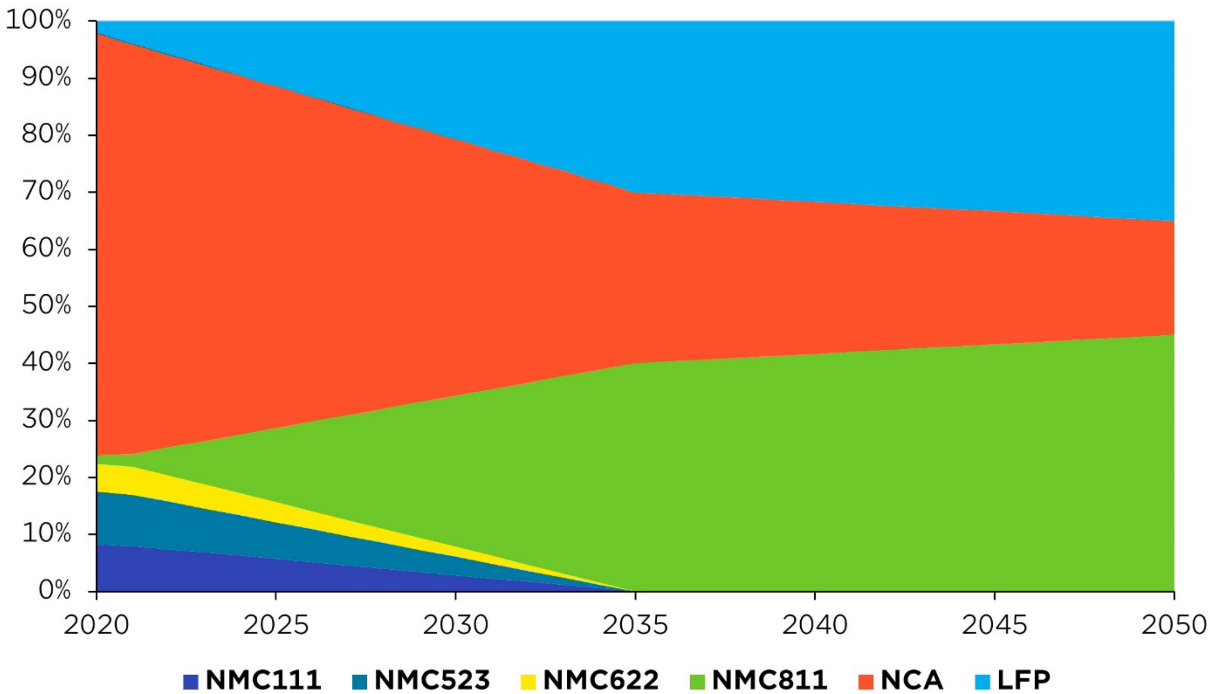
Table A.3. PHEV Light-Duty Car and Truck Battery Capacity (kWh)

Year	PHEV Car Capacity (kWh)	PHEV Truck Capacity (kWh)
2020	16	17
2021	16	17
2022	15	17
2023	16	17
2024	17	17
2025	17	17
2026	18	18
2027	18	18
2028	19	19
2029	19	19
2030	19	19
2031	20	20
2032	20	20
2033	21	21
2034	21	21
2035	22	22

PHEV sales phase out in 2035 as we transition to all electric. Therefore, we did not include average capacity from 2036 to 2050.

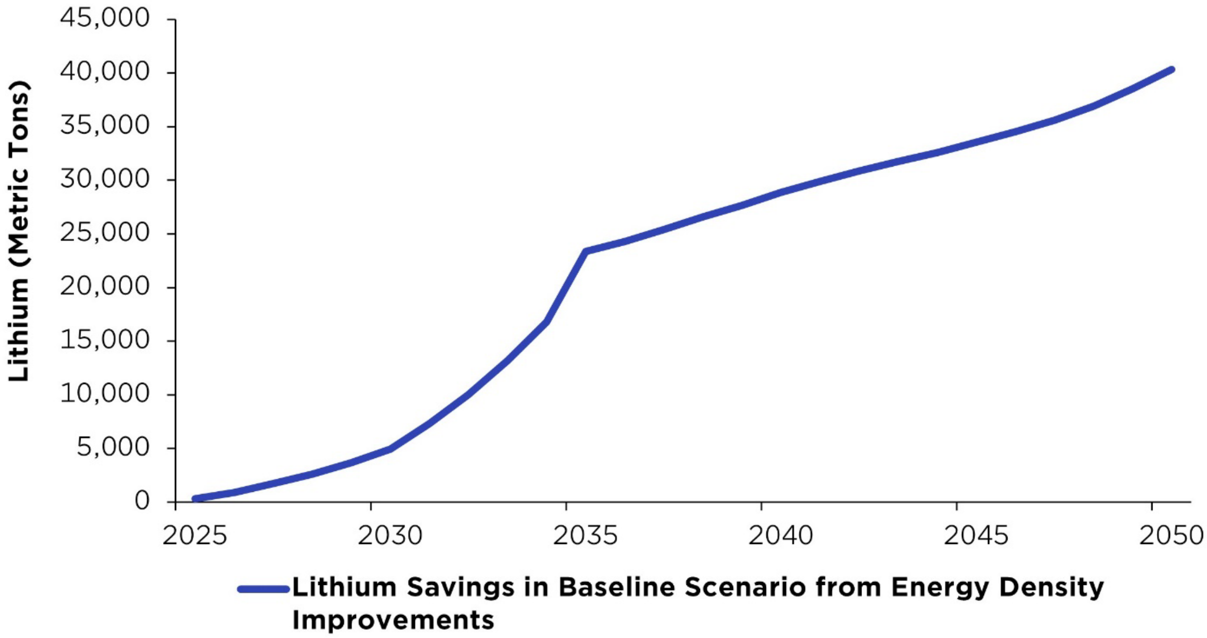
Future cathode chemistry is highly uncertain but will likely follow a transition to lower cobalt chemistries such as LFP, NCA, and NMC811 (BNEF 2023) (see Figure A.1). The cathode chemistry stoichiometry in Table A.4 was determined using BatPac from the Argonne National Laboratory (ANL 2023). The battery energy density is estimated to increase at a rate of 4 percent for every doubling of kWhs sold. This is based on recent findings that since 1990 energy density has had a learning rate of 6 percent for every doubling of kWh sales (Walter et al. 2024; Walter et al. 2023). These findings include an estimate that a third of this density increase is based on changes in cathode chemistry, while two-thirds are based on the energy density improvements of each chemistry. Because our analysis already forecasts a change in cathode chemistry to more energy-dense cobalt- and nickel-containing chemistries (i.e., NMC811 and NCA), we use a learning rate of 4 percent, not 6 percent. Figure A.2 demonstrates the impact this learning rate has on the mineral demand in the Baseline scenario. For the Very Low Demand scenario, we assume that future learning rates will be equivalent to best-of-class technology improvements, which have a total learning rate 1 percent higher—thus, a learning rate of 5 percent.

Figure A.1. Cathode Chemistry of Light-Duty EVs Forecasted until 2050



LFP gains market share while cobalt-containing chemistries (NCA and NMC) either stagnate or decline.

Figure A.2. Energy Density Gains Reduce Overall Mineral Needs in the Baseline Scenario



Battery energy density is estimated to increase at a rate of 4 percent for every doubling of kWhs sold. This estimate is based on historical density improvements (Walter et al. 2024; Walter et al. 2023). The graph demonstrates the impact of energy density gains on the Baseline scenario used in our analysis.

Table A.4. Cathode and Anode Stoichiometry of Lithium-Ion Battery Chemistries in 2023 and Prior to Energy Density Gains

Cathode	Lithium	Nickel	Cobalt	Manganese	Aluminum	Copper	Graphite
NMC111	0.141	0.351	0.352	0.328	3.110	0.677	0.978
NMC523	0.136	0.508	0.204	0.285	3.070	0.661	0.981
NMC622	0.118	0.531	0.178	0.166	3.017	0.605	0.960
NMC811	0.100	0.600	0.075	0.070	2.921	0.549	0.961
NCA	0.102	0.672	0.127	0.000	2.920	0.564	0.978
LMO	0.106	0.000	0.000	1.396	3.369	0.863	0.911
LFP	0.095	0.000	0.000	0.000	3.528	0.946	1.850

Note: The kg/kWh of minerals in lithium-ion batteries sourced from Argonne National Lab (ANL 2023).

Alternative Battery Technology

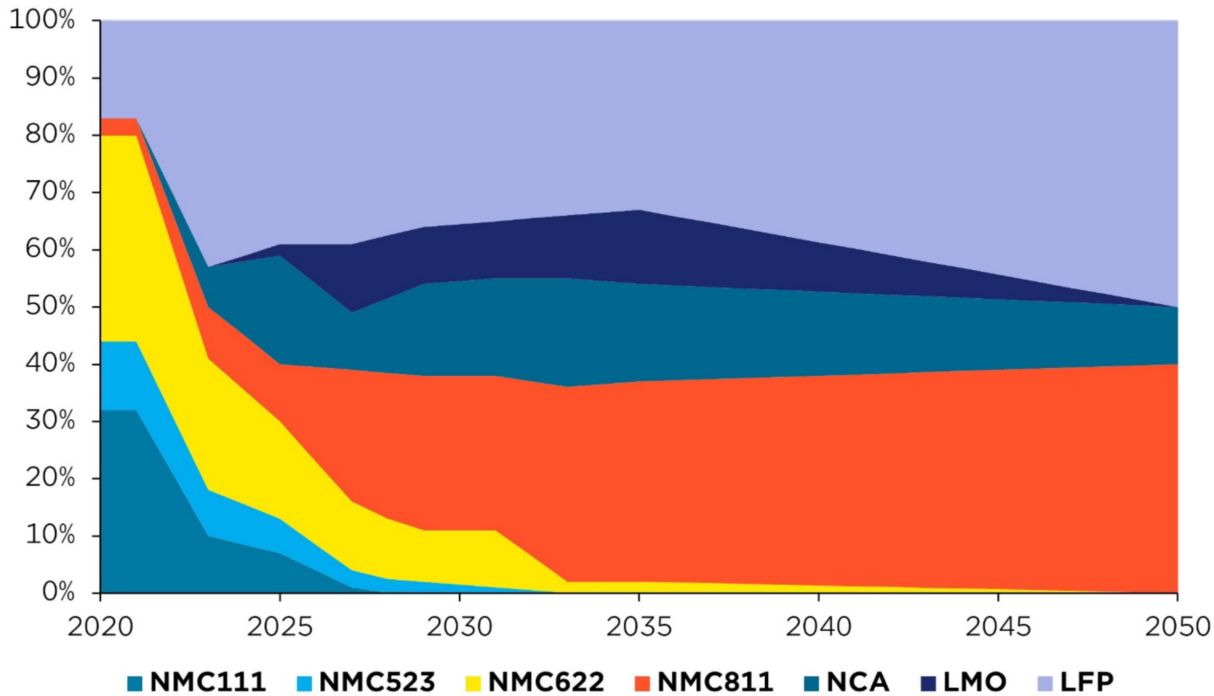
There is huge potential for battery design, material substitution, and other breakthroughs to continue drastically changing future mineral needs. Not included in this paper is the increased market share of non-lithium alternatives, such as sodium-ion batteries. These batteries use sodium, which is ubiquitous and relatively inexpensive, instead of lithium. Currently, they have low energy density and are, therefore, unable to provide the necessary range for mass-market EVs in the United States, but they can be a good substitute for lower-range models (Hanley 2024). Research is being done to increase their density, and if this is achieved, sodium could displace a higher portion of lithium demand (Maisch 2024).

The use of solid-state batteries, which use a solid electrolyte instead of a liquid one, could also change mineral forecasts. This technology is not yet on the EV market, but there have recently been prototypes demonstrating potential energy density gains and the ability to use lithium anodes in EV batteries (QuantumScape 2024; Sun, Ouyang, and Hao 2022). Overall, the use of solid state is likely to reduce nickel and cobalt demand but slightly increase the use of lithium, as it would be used in the anode as well as the cathode (Xu et al. 2020). While we include increased density in this analysis, the use of lithium in the anode is not included in the research.

A.2. Transit Characteristics

We calculated the US sales-weighted average electric transit bus battery capacity (kWh) from 2017 to 2024 (S&P 2024). From 2025 to 2035, battery capacity estimates for transit bus (class 6, 7, and 8) from the International Council on Clean Transportation (ICCT) are used (O'Connell et al. 2023). Following the trend found by the ICCT, we used linear regression to forecast trendlines from 2035 to 2050. The battery capacity used for hybrid transit buses is estimated to be 20 kWh for all years, based on an assessment of hybrid battery size, typically ranging from 11 to 32 kWh depending on make and model (California ARB 2024). The cathode chemistry forecast is based on estimates from Bloomberg of battery chemistry from 2020 to 2035. It is extended to 2050, following similar trends of increased LFP and lower cobalt chemistries (BNEF 2023). The transit bus battery capacity estimates are in Table A.5 and the cathode chemistry forecast is in Figure A.3.

Figure A.3. Transit Bus Cathode Chemistry Forecast



LFP continues to represent a large market share, and cobalt-containing chemistries (NCA and NMC) begin to increase to a proportional share.

Table A.5. Transit Bus Battery Capacity

Year	EV Transit Bus Battery Size (kWh)	Year	EV Transit Bus Battery Size (kWh)
2020	500	**2036**	377
2021	493	**2037**	376
2022	493	**2038**	371
2023	510	**2039**	366
2024	471	**2040**	361
2025	435	**2041**	357
2026	431	**2042**	352
2027	426	**2043**	347
2028	421	**2044**	342
2029	416	**2045**	337
2030	406	**2046**	332
2031	403	**2047**	327
2032	400	**2048**	323
2033	396	**2049**	317
2034	393	**2050**	313
2035	390		

A.3. Decreased EV Sales as a Result of Increased Mobility Options

The 2023 UCS Accelerating Clean Energy Ambition (ACEA) report estimates changes in the energy system needed to meet zero-emission goals by 2050, including the transportation sector (Pinto de Moura 2024). Total vehicle sales are put into ACEA modeling, and the stock shares for each technology are determined by the stock rollover from the AEO (EIA 2023). ACEA modeling then finds the lowest-cost technology mix to achieve the desired goals.

For the Baseline scenario in this paper, the ACEA sales forecast from the House Select Committee Case were used (Clemmer et al. 2023). This assumes all light-duty vehicle sales are electrified by 2035 and transit vehicle sales are electrified by 2040. The ACEA model includes two scenarios that reduce transportation demand (VMT) from light-duty vehicles by increasing transit and rail demand, as outlined in Table A.6.

The per capita VMT reduction used in the Very Low Demand scenario is in line with and even more conservative than some of the most ambitious VMT reduction goals in the United States. For example, Washington State aims to reduce VMT per capita by 30 percent by 2035 and 50 percent by 2050 (Washington State Legislature 2024), California aims to reduce VMT per capita by 25 percent by 2035 and 30 percent by 2045 from 2019 levels(California ARB 2022), Maine aims to reduce statewide light-duty VMT by 20 percent by 2030 (Maine Climate Council 2020), Delaware aims to reduce VMT by 10 percent by 2030 (Delaware DNREC 2021), and Connecticut aims to reduce VMT per capita by 5 percent by 2030 (Connecticut DOT 2023). Research by the ICCT takes a different approach, focusing on VMT reduction in cities and estimating feasible VMT reductions of 35 percent per capita in US cities by 2050 (Sen et al. 2023). A large body of academic literature recognizes similar levels of VMT reductions in the US as ambitious but feasible; this literature is summarized in Hoehne et al. (2023). We assume population growth using EIA projections of 12.3 percent growth from 2023 to 2050.

Table A.6. ACEA scenarios that Vary VMT and Car Ownership Rates

	Baseline (2050) (Car Dependent)	Low Mineral Demand (2050) (Low VMT)	Very Low Mineral Demand (2050) (Ambitious VMT Reduction)
Light-Duty VMT	+21% total from 2023 +8% per capita from 2023 +0.71% average total per year VMT growth from 2023 to 2050	-3% total from 2023 -14% per capita from 2023 -0.12% average total per year VMT growth from 2023 to 2050	-27% total from 2023 -35% per capita from 2023 -1.18% average total per year VMT growth from 2023 to 2050
Transit/Intercity Bus VMT and Passenger Rail Passenger Miles Traveled (PMT)	----- +19% bus VMT from 2023 -27% passenger rail PMT from 2023	+50% from 2050 Baseline +78% bus VMT from 2023 +9% passenger rail PMT from 2023	+100% from 2050 Baseline +137% bus VMT from 2023 +45% passenger rail PMT from 2023

This analysis aims to determine if transportation system changes that lead to decreased sales of light-duty vehicles and increased sales of transit buses lead to an overall decrease in the minerals needed to electrify passenger transportation. While ACEA has scenario assumptions for VMT changes for the Low Mineral Demand and Very Low Demand scenarios, we must translate these to the number of light-duty vehicles and transit buses sold per year, numbers not produced by the ACEA model. This process is discussed in the next section.

Establishing a Link between Light-Duty VMT and Car Ownership

Next in the modeling process, we establish the relationship between VMT and car ownership: if we reduce VMT, how many fewer cars will be on the road? There is inherent uncertainty in this relationship based on how VMT reductions are implemented, but we use a regression analysis that isolates this relationship as it is affected by the built environment, controlling for socioeconomic factors.

We use Center for Neighborhood Technology's (CNT) Housing and Transportation Affordability Index data, which contain block-group level estimates of household VMT, auto ownership, and transit use, as well as resulting cost burdens for 2016 and 2019 (CNT 2019). CNT's numbers estimate this for a "typical" national household to control for the effects of income, household size, and commuters per household, meaning that changes are largely reflected by a change in environment. We then specify a population-weighted regression model as follows:

$$\Delta LDVpercap = \beta \Delta VMTpercap + \epsilon$$

Where $\Delta LDVpercap$ represents the change in vehicle ownership per capita between 2016 and 2019, $\Delta VMTpercap$ represents the change in VMT per capita between 2016 and 2019, β represents the effects of changes in VMT per capita on vehicle ownership, and ϵ represents the regression residual.

By regressing on differences between 2016 and 2019, we take a marginal approach, capturing the VMT and vehicle ownership relationship representative of changes in the present situation, such as by built environment or policy changes that reduce VMT. This is taken in favor of an average approach, which would assume that changes in VMT would result in reducing car ownership by their average VMT. This more accurately captures the effects of future changes in VMT, and also matches the framing of ACEA modeling. The average approach does not take into account the high friction of buying and selling a vehicle and also overweighs initial vehicle VMT, which is more inelastic and less susceptible to change than more marginal decisions (i.e., if new policies were to take effect in the coming years).

We benchmark this estimate with several other modeling methodologies and model specifications (and marginal vs. average), using DOT's LATCH dataset, which comes from bottom-up survey data in the National Household Travel Survey (BTS 2021), as well as the US Federal Highway Administration's Highway Statistics Series, which come from system-level registration data and state DOT VMT measurements and estimates (FHA 2022). While these datasets do come from bottom-up estimates, they do not allow for isolation of transportation and land-use variables, and they also do not have neighborhood-level geographic specificity that would best represent the effects of built environment factors.

Table A.7. Effects of Changing VMT on Car Ownership

	CNT Method	Total US Using HPMS Data, 1994-2019 (available years)	Total US, HPMS, State Fixed Effects, 1994–2019	Total US, HPMS, State Fixed Effects, Recent Years (2010–2019)	LATCH Marginal Analysis, Income Controls
Effect of Annual VMT/Person on LDV/Person (expressed as 1/β; VMT per vehicle)	29,412***	15,151***	36,101***	78,740**	14,805***

The effect of annual VMT/person on light-duty vehicle (LDV)/person (expressed as 1/β; VMT per vehicle) is compared between data sources. We use the CNT methodology in our analysis.
*Note: ** means P ≤ 0.01, *** means P ≤ 0.001*

We then use this factor to reduce vehicle stock from our Baseline scenario by the appropriate amounts for the Low Mineral Demand and Very Low Mineral Demand scenarios based on light-duty vehicle VMT reductions.

Estimates for Bus Stock Increases from Increased Transit Service

Although VMT reductions can come through various strategies, we assume an associated increase of transit and rail service to offset some of the decreases in light-duty VMT in our ACEA report, listed above.

To estimate the changes in bus stock from increases in transit service, we leverage data from the American Public Transportation Association's (APTA) Public Transportation Fact Book (national level) and the US Federal Transit Administration's National Transit Database (agency level) (APTA 2023; FTA 2022a). Based on the scope of our minerals analysis, we chose not to analyze rail (aka fixed guideway transit) effects and focused on buses, utilizing bus VMT changes. Similarly, given the limited transit inputs into ACEA's modeling, we chose not to model the effects of demand response, vanpool, and trolleybus modes, given that buses make up a majority of the vehicle revenue miles (VRM) from transit.

Since NTD includes bus VRM instead of bus VMT, and given differences in data availability in their datasets, we make a modeling assumption for a percentage of bus VMT that is VRM, using Tables 8 and 11 in the APTA data, and apply that to all agencies. Given their similarity across time and all bus modes (bus, bus rapid transit, and commuter bus), we use 86.7 percent, which represents a VMT-weighted average of VRM to VMT by bus mode across 1995 to 2020. The full dataset shows how that varies, especially across differences such as between bus rapid transit and commuter buses, which are in revenue service for more of their mileage.

Using NTD Table 4.1 Asset Inventory Time Series (FTA 2022b) and Table 2.1 Service Data and Operating Expenses Time Series (FTA 2022c), we investigate the spread of VMT/bus across different agencies for all bus modes and find a weighted average, and in doing so also use the same average VMT per bus across all transit bus technologies (e.g., diesel, hybrid, natural gas, and battery electric). While we do observe a slightly larger variance of VMT per bus from 2014 to 2019 when weighted by agency bus fleet size, they are largely consistent.

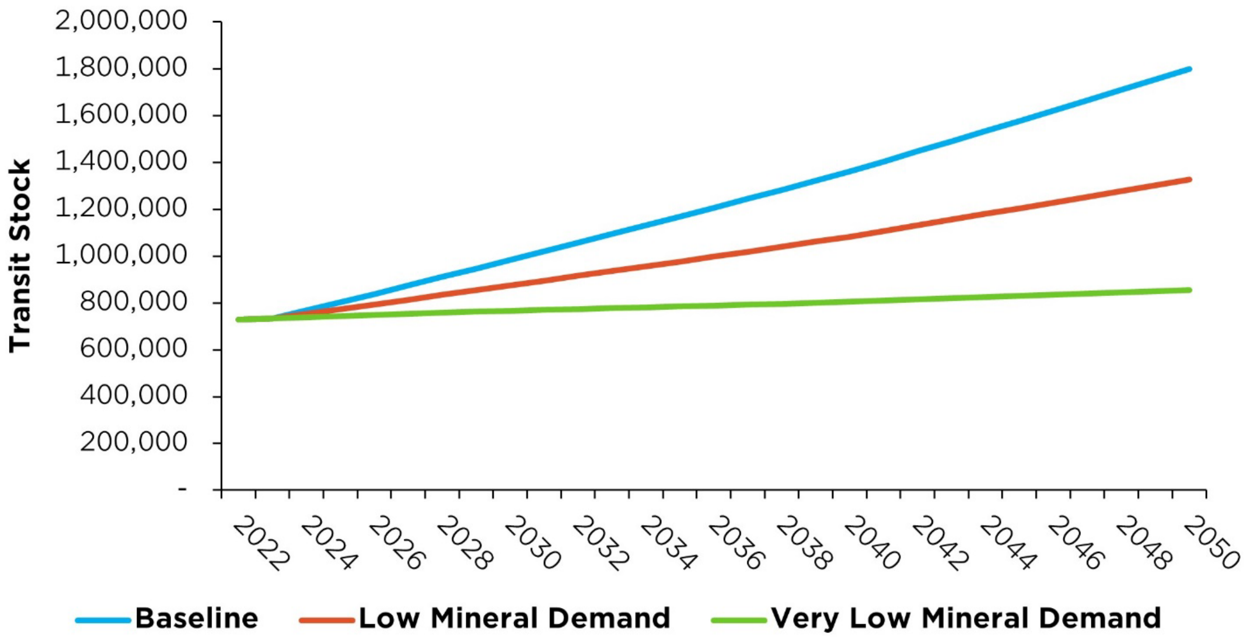
We also calculated a transit industry–wide average marginal VMT per bus, reflecting the effects of purchasing and selling buses as fleets stand now, rather than starting from scratch, which would exclude the more inelastic back-bone services that comprise many transit agencies' core service. Marginal approaches, as outlined above in the case of personal vehicle ownership, can be more representative in modeling future scenarios. After a regression model with year and agency fixed effects, we found that there is a 10,605 (186.8 std error) VMT/bus at the margin. This represents the effect if such services come online in future scenarios. This effect is also more statistically robust than the average approach above, but there is an open discussion on the use of average vs. marginal rates for these timescales. The model specification for this is:

$$Agency\ Bus\ VMT = \beta\ (Agency\ Bus\ Stock) + year\ fixed\ effect + agency\ fixed\ effect$$

β = the desired effect of VMT per bus, weighted by agency bus stock

We use this number to translate bus VMT to stock increases using the same process as the automobile data—using the change in bus VMT from the Baseline scenario to calculate a change in bus stock (i.e., using a marginal approach).

Figure A.4. Total Transit Bus Stock in the Three Scenarios



Note: The Very Low Mineral Demand Scenario is equivalent to the IRA Reference scenario from ACEA.

Translating Vehicle Stock Scenarios to Vehicle Sales

Now that we have light-duty vehicle and public transit stock numbers for all three scenarios, we must translate them to yearly vehicle sales using a yearly survival rate. We begin these calculations using the AEO National Energy Modeling System sales and stock forecast (EIA 2023), optimizing for yearly survival rates. To do this, we minimize the sum of squares of differences (similar to a regression) between estimated vehicle sales from a simplified stock turnover model based on VISION (ANL 2022) and reference vehicle sales in each year in the Baseline scenario. The survival rate used is in Table A.8; it represents the probability of a new vehicle surviving to age x+1, given that a vehicle has survived to age x. This survival rate is applied to the calculated stock numbers for the Baseline, Low Mineral Demand, and Very Low Mineral Demand scenarios. We also use the survival rate to calculate the number of vehicles retiring per year.

Table A.8. Yearly Survival Rates Used to Determine Vehicle Fleet Turnover

Retirement Year	Light-Duty Survival Rate	Transit Bus EV Survival Rate	Transit Bus Hybrid Survival Rate
0	0.990	1.000	1.000
1	0.990	1.000	1.000
2	0.990	1.000	1.000
3	0.990	1.000	1.000
4	0.990	1.000	0.960
5	0.990	1.000	0.849
6	0.990	0.999	0.837
7	0.990	0.989	0.815
8	0.990	0.950	0.904
9	0.980	0.950	0.964
10	0.970	0.516	0.834
11	0.950	0.379	0.772
12	0.930	0.333	0.805
13	0.930	0.046	0.861
14	0.930	0.000	0.895
15	0.930	0.000	0.824
16	0.733	0.000	0.735
17	0.565	0.000	0.625
18	0.473	0.000	0.237
19	0.417	0.000	0.000
20	0.371	0.000	0.000
21	0.326	0.000	0.000
22	0.283	0.000	0.000
23	0.246	0.000	0.000
>23	0.207	0.000	0.000

Table A.9. Light-Duty EV and PHEV Sales per Year

Year	Baseline	Low Mineral Demand	Very Low Mineral Demand
2024	2,206,768	2,183,224	2,159,681
2025	2,641,327	2,602,576	2,563,825
2026	3,593,025	3,530,288	3,467,551
2027	4,535,526	4,440,882	4,346,237
2028	5,468,861	5,334,497	5,200,133
2029	6,392,938	6,218,076	6,035,448
2030	7,377,392	7,160,066	6,920,060
2031	9,522,428	9,185,495	8,850,998
2032	11,572,512	11,132,693	10,691,893
2033	13,699,721	13,122,104	12,552,958
2034	15,869,633	15,139,091	14,415,437
2035	17,985,276	17,108,865	16,232,454
2036	17,905,157	16,926,644	15,948,130
2037	17,888,056	16,815,199	15,742,341
2038	17,910,558	16,745,545	15,580,531
2039	17,889,498	16,650,266	15,411,034
2040	17,868,438	16,554,987	15,241,537
2041	17,847,377	16,459,709	15,072,040
2042	17,826,317	16,364,430	14,902,543
2043	17,805,257	16,269,151	14,733,046
2044	17,784,196	16,173,873	14,563,549
2045	17,855,239	16,184,940	14,514,641
2046	17,918,431	16,150,719	14,383,008
2047	18,033,245	16,189,746	14,346,246
2048	18,249,604	16,347,618	14,445,632
2049	18,621,826	16,693,800	14,765,773
2050	19,048,567	16,929,168	14,809,768

Table A.10. Light-Duty EV Vehicle Sales per Year

Year	Baseline	Low Demand	Very Low Demand
2024	2,059,336	2,038,437	2,017,539
2025	2,485,922	2,450,726	2,415,529
2026	3,448,555	3,390,225	3,331,894
2027	4,402,361	4,312,820	4,223,279
2028	5,349,636	5,220,902	5,092,169
2029	6,287,033	6,110,470	5,933,906
2030	7,275,605	7,041,958	6,808,311
2031	9,418,959	9,090,719	8,762,478
2032	11,493,680	11,058,641	10,623,602
2033	13,642,505	13,078,458	12,514,411
2034	15,846,313	15,126,961	14,407,610
2035	17,985,276	17,108,865	16,232,454
2036	17,905,157	16,926,644	15,948,130
2037	17,888,056	16,815,199	15,742,341
2038	17,910,558	16,745,545	15,580,531
2039	17,889,498	16,650,266	15,411,034
2040	17,868,438	16,554,987	15,241,537
2041	17,847,377	16,459,709	15,072,040
2042	17,826,317	16,364,430	14,902,543
2043	17,805,257	16,269,151	14,733,046
2044	17,784,196	16,173,873	14,563,549
2045	17,855,239	16,184,940	14,514,641
2046	17,918,431	16,150,719	14,383,008
2047	18,033,245	16,189,746	14,346,246
2048	18,249,604	16,347,618	14,445,632
2049	18,621,826	16,693,800	14,765,773
2050	19,048,567	16,929,168	14,809,768

Table A.11. Light-Duty PHEV Vehicle Sales per Year

Year	Baseline	Low Demand	Very Low Demand
2024	147,432	144,787	142,142
2025	155,405	151,850	148,296
2026	144,470	140,063	135,656
2027	133,165	128,062	122,958
2028	119,225	113,595	107,965
2029	105,904	107,607	101,542
2030	101,787	118,108	111,749
2031	103,469	94,777	88,520
2032	78,832	74,052	68,291
2033	57,217	43,646	38,547
2034	23,321	12,129	7,826
2035	0	0	0

Table A.12. Electric Transit Bus Sales per Year

Year	Baseline	Low Demand	Very Low Demand
2024	230	256	281
2025	348	402	455
2026	540	646	751
2027	794	985	1,177
2028	1,091	1,408	1,725
2029	1,495	1,999	2,504
2030	2,087	2,883	3,678
2031	2,791	3,970	5,150
2032	3,539	5,208	6,878
2033	4,302	6,556	8,810
2034	5,011	7,917	10,823
2035	5,684	9,301	12,917
2036	6,400	10,810	15,220
2037	7,045	12,272	17,498
2038	7,427	13,361	19,295
2039	7,592	14,101	20,610
2040	7,764	14,819	21,873
2041	8,155	15,849	23,543
2042	8,261	16,404	24,547
2043	8,292	16,812	25,332
2044	8,292	17,162	26,033
2045	8,307	17,545	26,783
2046	8,443	18,154	27,865
2047	8,591	18,800	29,009
2048	8,698	19,409	30,121
2049	8,718	19,892	31,066
2050	8,718	20,335	31,952

Table A.13. Hybrid Transit Bus Sales Forecast per Year

Year	Baseline	Low Demand	Very Low Demand
2024	792	1,324	1,855
2025	1,034	1,569	2,104
2026	1,497	2,032	2,567
2027	1,432	1,960	2,488
2028	1,348	1,884	2,420
2029	946	1,536	2,125
2030	766	1,385	2,005
2031	990	1,614	2,238
2032	975	1,550	2,124
2033	751	1,244	1,738
2034	465	908	1,352
2035	257	651	1,045
2036	218	533	847
2037	198	407	616
2038	176	284	393
2039	138	181	224
2040	0	0	0
2041	0	0	0
2042	0	0	0
2043	0	0	0
2044	0	0	0
2045	0	0	0
2046	0	0	0
2047	0	0	0
2048	0	0	0
2049	0	0	0
2050	0	0	0

A.4. Reuse, Repurposing, and Recycling

When an EV retires, the battery can be reused in a vehicle, repurposed in a different application, or recycled. We assume 90 percent of batteries retiring will be collected. At that point, it is assumed 30 percent of collected batteries are reused or repurposed, while 70 percent go directly to recycling. The percentage of batteries currently repurposed is unknown, therefore we base this percentage on research by Liao et al. (2017), who did a visual inspection of retired batteries, assessing whether they were damaged and suitable for further testing. Repurposed battery lifespan is dependent on many factors, including battery health and use (Casals, Amante Garcia, and Canal 2019). In this model, we estimate the repurposed batteries to have an average lifespan of 10 years, when they will be ready for recycling. We also estimate that if recalls are included, 3.5 percent of the batteries within light-duty vehicles will need to be replaced after five years (Najman 2023). Those batteries are expected to be replaced under warranty, skip reuse or repurposing, and go directly to recycling.

For the Baseline scenario, we assume not all recycling facilities and processes will recover lithium, resulting in an average recovery rate of 50 percent. The Low Demand scenario includes lithium recovery rates equal to EU requirements. The best available recycling technology is assumed to be used in the Very Low Demand scenario, resulting in the highest recovery rate. Recycling efficiency rates for the Very Low Demand scenario in Table A.14 represent hydrometallurgical recycling and were taken from the Argonne National Laboratory model EverBatt (ANL 2021).

Table A.14. Recycling Efficiency Rates Used in This Analysis

Mineral	Mineral Efficiency Use in the Baseline Scenario	Mineral Efficiency Use in the Low Demand Scenario	Mineral Efficiency Use in the Very Low Demand Scenario
Lithium	0.50	0.50 until 2030, 0.80 from 2031 to 2050	0.90
Nickel	0.98	0.98	0.98
Cobalt	0.98	0.98	0.98
Manganese	0.98	0.98	0.98
Aluminum	0.90	0.90	0.90
Copper	0.90	0.90	0.90
Graphite	0.90	0.90	0.90

A.5. Model Results

Table A.15. Summarized Lithium Demand Model Results

Metric	Baseline	Low Demand	Very Low Demand
Lithium Demand in 2050 (metric tons)	178,277	130,597	91,995
Percent Decrease in Lithium Demand from 2050 Compared to Baseline		27%	48%
Lithium Demand Decrease in 2050 Compared to Baseline (metric tons)		47,680	86,282
Lithium Recycled Content in 2050	26%	47%	59%
Newly Mined Lithium Demand in 2050 (metric tons)	131,043	69,885	37,664
Percent Decrease in Newly Mined Lithium in 2050 Compared to Baseline		47%	71%
Cumulative Lithium Demand 2025–2050 (metric tons)	3,534,870	2,752,568	2,124,628
Percent Decrease in Lithium Demand from 2025–2050 Compared to Baseline		22%	40%
Lithium Demand Decrease from 2025–2050 Compared to Baseline (metric tons)		782,302	1,410,242
Recovered Lithium from Recycling from 2025–2050 (metric tons)	379,195	505,964	474,560
Newly Mined Cumulative Lithium Demand 2025–2050 (metric tons)	3,155,675	2,246,604	1,650,068
Percent Decrease in Newly Mined Lithium from 2025–2050 Compared to Baseline		29%	48%
Newly Mined Lithium Demand Decrease from 2025–2050 Compared to Baseline (metric tons)		909,071	1,505,607

This table provides the summarized results for lithium demand, recycled content availability, and percent decrease of newly mined minerals for the three scenarios.

Table A.16. Lithium Demand of Implementing One Reduction Strategy

Scenario	Cumulative Demand 2025-2050	Percent Decrease from Baseline Cumulative Demand for Years 2025-2050	Cumulative Demand 2025-2035	Percent Decrease from Baseline Cumulative Demand for Years 2025-2035
Baseline	3,529,597		908,564	
10% efficiency gain	3,197,128	9%	858,363	6%
300 mile range	3,292,802	7%	872,764	4%
14% reduction VMT	3,275,441	7%	874,774	4%
20% efficiency gain	2,746,263	22%	782,035	14%
275 mile range	2,812,826	20%	796,088	12%
35% reduction VMT	2,997,795	15%	834,432	8%
+1% increase in energy density	3,141,404	11%	846,288	7%

A 20 percent increase in EV efficiency leads to the highest reduction—20 percent—of overall mineral demand from 2020 to 2050. This is followed by reducing the range to 275 miles, resulting in 20 percent lower mineral demand.

Table A.17. Model Results, Including Demand and Retirement of Light-Duty and Transit Batteries, Represented as GWh and Metric Tons of Lithium, Cobalt, and Nickel

	Year	Baseline	Low Demand	Very Low Demand
GWh Demand	2030	619	558	497
GWh Demand	2040	1,826	1,395	1,089
GWh Demand	2050	1,945	1,425	1,057
Lithium Demand	2030	67,320	60,016	52,391
Lithium Demand	2040	176,924	133,573	100,780
Lithium Demand	2050	178,277	130,597	91,995
Nickel Demand	2030	322,273	287,093	250,393
Nickel Demand	2040	740,640	558,596	420,948
Nickel Demand	2050	706,888	517,448	364,145
Cobalt Demand	2030	62,619	55,783	48,652
Cobalt Demand	2040	112,335	84,723	63,845
Cobalt Demand	2050	103,434	75,713	53,280
Lithium Recovered	2030	2,383	2,164	3,465
Lithium Recovered	2040	13,601	18,486	17,569
Lithium Recovered	2050	46,233	60,742	54,331
Nickel Recovered	2030	22,789	20,703	18,461
Nickel Recovered	2040	124,356	106,736	91,036
Nickel Recovered	2050	406,471	335,472	267,934
Cobalt Recovered	2030	4,665	4,253	3,810
Cobalt Recovered	2040	23,169	20,265	17,610
Cobalt Recovered	2050	67,393	56,073	45,158

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References

Ambrose, Hanjiro, and Alissa Kendall. 2016. "Effects of Battery Chemistry and Performance on the Life Cycle Greenhouse Gas Intensity of Electric Mobility." Transportation Research Part D: Transport and Environment 47:182–94. https://doi.org/10.1016/j.trd.2016.05.009

Ambrose, Hanjiro, and Alissa Kendall. 2020. "Understanding the Future of Lithium: Part 1, Resource Model." Journal of Industrial Ecology 24 (1): 80–89. https://doi.org/10.1111/jiec.12949

ANL (Argonne National Lab). 2021. "EverBatt: Argonne's Closed-Loop Battery Life-Cycle Model." Accessed September 1, 2021. https://www.anl.gov/egs/everbatt

ANL (Argonne National Lab). 2022. "VISION Model." Accessed October 1, 2024. https://www.anl.gov/egs/everbatt

ANL (Argonne National Laboratory). 2023. "BatPaC: Battery Manufacturing Cost Estimation." Accessed January 9, 2024. https://www.anl.gov/tcp/batpac-battery-manufacturing-cost-estimation

APTA (American Public Transportation Association). 2023. "Public Transportation Fact Book." Accessed June 30, 2024. https://www.apta.com/wp-content/uploads/APTA-2023-Public-Transportation-Fact-Book.pdf

Archer, Deborah N. 2020. "'White Men's Roads through Black Men's Homes': Advancing Racial Equity through Highway Reconstruction." Vanderbilt Law Review 73: 1259–1330. https://scholarship.law.vanderbilt.edu/vlr/vol73/iss5/1

Atlas. 2024. "EV Sales." Accessed February 26, 2024. https://www.atlasevhub.com/materials/automakers-dashboard/

Biden-Harris (Biden-Harris Administration's Interagency Working Group on Mining Laws Regulations and Permitting). 2023. "Recommendations to Improve Mining on Public Lands." Accessed July 1, 2024. https://www.doi.gov/media/document/mriwg-report-final-508-pdf

Block, Samuel. 2021. "Mining Energy-Transition Metals: National Aims, Local Conflicts." MSCI (blog). June 3. https://www.msci.com/www/blog-posts/mining-energy-transition-metals/02531033947

BNEF (Bloomberg New Energy Finance). 2023. "Electric Vehicle Outlook 2023." Accessed February 4, 2024. https://assets.bbhub.io/professional/sites/24/2431510_BNEFElectricVehicleOutlook2023_ExecSummary.pdf

BTS (United States Bureau of Transportation Statistics). 2021. "Local Area Transportation Characteristics for Households." Accessed June 30, 2024. https://www.bts.gov/latch

BTS (United States Bureau of Transportation Statistics). 2024. "The Household Cost of Transportation: Is It Affordable?" Accessed July 24, 2024. https://www.bts.gov/data-spotlight/household-cost-

transportation-it-affordable
California ARB (Air Resources Board). 2022. “2022 Scoping Plan for Achieving Carbon Neutrality.” Accessed July 31, 2024. https://ww2.arb.ca.gov/sites/default/files/2022-12/2022-sp_1.pdf
California ARB (Air Resources Board). 2024. “Bus Inventory Data.” Accessed July 31, 2024. https://ww2.arb.ca.gov/our-work/programs/innovative-clean-transit/reporting-tool-data
Casals, Lluc Canals, B. Amante García, and Camille Canal. 2019. “Second Life Batteries Lifespan: Rest of Useful Life and Environmental Analysis.” Journal of Environmental Management 232: 354–63. https://doi.org/10.1016/j.jenvman.2018.11.046
Ciez, Rebecca E., and J. F. Whitacre. 2017. “Comparison between Cylindrical and Prismatic Lithium-Ion Cell Costs Using a Process Based Cost Model.” Journal of Power Sources 340: 273–81. https://doi.org/10.1016/j.jpowsour.2016.11.054
Clemmer, Steve, Rachel Cleetus, Jeremy Martin, Maria Cecilia P. Moura, Paul Arbaje, Maria Chavez, and Sandra Sattler. 2023. “Accelerating Clean Energy Ambition: How the US Can Meet Its Climate Goals While Delivering Public Health and Economic Benefits.” Accessed October 1, 2024. https://doi.org/10.47923/2023.15253
CNT (Center for Neighborhood Technology). 2019. “The Housing and Transportation (H+T) Affordability Index.” Accessed June 30, 2024. https://htaindex.cnt.org/
Connecticut DOT (Department of Transportation). 2023. “2030 VMT Goal and Strategies.” Accessed August 1, 2024. https://portal.ct.gov/-/media/dot/documents/dpolicy/vmt-reduction-target.pdf
Del Pero, Francesco, Massimo Delogu, and Marco Pierini. 2018. “Life Cycle Assessment in the Automotive Sector: A Comparative Case Study of Internal Combustion Engine (ICE) and Electric Car.” Procedia Structural Integrity 12: 521–37. https://doi.org/10.1016/j.prostr.2018.11.066
Delaware DNREC (Department of Natural Resources and Environmental Control). 2021. “Delaware’s Climate Action Plan Was Prepared by the Delaware Department of Natural Resources and Environmental Control.” Accessed August 1, 2024. https://documents.dnrec.delaware.gov/energy/Documents/Climate/Plan/Delaware-Climate-Action-Plan-2021.pdf
Dunn, Jessica, Alissa Kendall, and Margaret Slattery. 2022. “Electric Vehicle Lithium-Ion Battery Recycled Content Standards for the US: Targets, Costs, and Environmental Impacts.” Resources, Conservation and Recycling 185 (October): 106488. https://doi.org/10.1016/j.resconrec.2022.106488
Dunn, Jessica, Kabian Ritter, Jesús M. Velázquez, and Alissa Kendall. 2023. “Should High-Cobalt EV Batteries Be Repurposed? Using LCA to Assess the Impact of Technological Innovation on the Waste Hierarchy.” Journal of Industrial Ecology 27 (5): 1277–1290. https://doi.org/10.1111/jiec.13414
Dunn, Jessica, Margaret Slattery, Alissa Kendall, Hanjiro Ambrose, and Shuhan Shen. 2021. “Circularity of Lithium-Ion Battery Materials in Electric Vehicles.” Environmental Science and Technology 15 (8): 5189–98. https://doi.org/10.1021/acs.est.0c07030
Earthworks. 2024. “1872 Mining Law: Reform Requirements.” Accessed July 1, 2024. https://earthworks.org/issues/1872-mining-law-reform-requirements/#:~:text=Under%20a%20reformed%20mining%20law,civil%20and%20criminal%20penalty%20assessments
EIA (United States Energy Information Administration). 2023. “Annual Energy Outlook.” Accessed October 10, 2024. https://www.eia.gov/outlooks/aeo/
EIA (United States Energy Information Administration).2024. “Frequently Asked Questions (FAQs): US Energy Information Administration (EIA).” 2024. Accessed October 10, 2024. https://www.eia.gov/tools/faqs/faq.php?id=23&t=10
Electric and Hybrid Vehicle Battery Management Act, Bill S3723, 2023. New Jersey Senate (2024). https://www.njleg.state.nj.us/bill-search/2022/S3723/bill-text?f=S4000&n=3723_I1
English, Jonathan. 2018. “Why Did America Give Up on Mass Transit? (Don’t Blame Cars.).” Bloomberg, August 31, 2018. https://www.bloomberg.com/news/features/2018-08-31/why-is-american-mass-transit-so-bad-it-s-a-long-story
EP&C (The European Parliament and of the Council). 2023. “Regulation (EU) 2023/1542 Concerning Batteries and Waste Batteries, Amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and Repealing Directive 2006/66/EC.” Accessed October 10, 2024. https://eur-lex.europa.eu/eli/reg/2023/1542/oj

EPA (United States Environmental Protection Agency). 2023a. “Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles.” Accessed October 10, 2024. https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-multi-pollutant-emissions-standards-model
———. 2023b. “The 2022 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975.” Accessed October 10, 2024. https://www.epa.gov/system/files/documents/2023-12/420r23033.pdf
EPA (United States Environmental Protection Agency). 2024. “Www.Fueleconomy.Gov.” Accessed October 10, 2024. https://www.fueleconomy.gov/feg/PowerSearch.do?action=noform&path=3&year1=2021&year2=2023&vtype=Electric&srchtyp=newAfv&pageno=1&rowLimit=50
EPRI-NRDC (Electric Power Research Institute and Natural Resource Defense Council). 2024. “Valuing Improvements in Electric Vehicle Efficiency.” Accessed October 10, 2024. https://esca.epri.com/Decarbonization-Pathways-and-Impacts.html
FHA (United States Federal Highway Administration). 2022. “Highway Statistics Series.” Accessed October 10, 2024. https://www.fhwa.dot.gov/policyinformation/statistics.cfm
FHA (United States Federal Highway Administration). 2023. “FHWA Forecasts of Vehicle Miles Traveled (VMT): Spring 2023.” Accessed October 10, 2024. https://www.fhwa.dot.gov/Policyinformation/tables/vmt/2023_vmt_forecast_sum.pdf
FTA (United States Federal Transit Administration). 2022a. “National Transportation Database.” Accessed October 10, 2024. https://www.transit.dot.gov/ntd/ntd-data
———. 2022b. “TS4.1: Asset Inventory Time Series.” Accessed October 10, 2024. https://www.transit.dot.gov/ntd/data-product/ts41-asset-inventory-time-series-4
———. 2022c. “TS2.1: Service Data and Operating Expenses Time Series by Mode.” Accessed October 10, 2024. https://www.transit.dot.gov/ntd/data-product/ts21-service-data-and-operating-expenses-time-series-mode-2
FTS (Foundation of Traffic Safety). 2022. “American Driving Survey: 2022.” Accessed December 13, 2024. https://aaafoundation.org/wp-content/uploads/2023/09/202309_2022-AAAFTS-American-Driving-Survey-Brief_v3.pdf
Gaines, Linda, Qiang Dai, John T. Vaughey, and Samuel Gillard. 2021. “Direct Recycling R&D at the ReCell Center.” Recycling 6 (31): 13–18. https://doi.org/10.3390/recycling6020031
GAO (United States Government Accountability Office). 2005. “Hardrock Mining: BLM Needs to Better Manage Financial Assurances to Guarantee Coverage of Reclamation Costs.” Accessed October 10, 2024. www.gao.gov/cgi-bin/getrpt?GAO-05-377
Hanley, Steve. 2024. “Electric Cars Powered by Sodium Ion Batteries Go On Sale In China.” Clean Technica, January 22, 2024. https://cleantechnica.com/2023/12/29/electric-cars-powered-by-sodium-ion-batteries-go-on-sale-in-china/
Heggedal, Kristina. 2023. “Promoting Transportation Options and Measuring with a VMT Target.” Accessed July 31, 2024. https://metrocouncil.org/Council-Meetings/Work-Groups/TPP-Technical-Working-Group/2023/2023-09-14-TPP-Technical-Working-Group-Meeting/2023-09-14-TPP-TWG-Presentation-VMT-Follow-up.aspx
Hoehne, Christopher, Matteo Muratori, Paige Jadun, Brian Bush, Arthur Yip, Catherine Ledna, Laura Vimmerstedt, Kara Podkaminer, and Ookie Ma. 2023. “Exploring Decarbonization Pathways for USA Passenger and Freight Mobility.” Nature Communications 14 (1). https://doi.org/10.1038/s41467-023-42483-0
Huether, Peter. 2024. “Electric Vehicle Efficiency: Unlocking Consumer Savings and Environmental Gains.” Accessed August 21, 2024. https://www.aceee.org/white-paper/2024/08/electric-vehicle-efficiency-unlocking-consumer-savings-and-environmental-gains
IEA (International Energy Agency). 2024. “Global EV Outlook 2024: Moving towards Increased Affordability.” Accessed October 10, 2024. https://www.iea.org/reports/global-ev-outlook-2024
Klimenko, V. V., S. V. Ratner, and A. G. Tereshin. 2021. “Constraints Imposed by Key-Material Resources on Renewable Energy Development.” Renewable and Sustainable Energy Reviews 144 (July): 1–13. https://doi.org/10.1016/j.rser.2021.111011
Liang, Yanan, René Kleijn, and Ester van der Voet. 2023. “Increase in Demand for Critical Materials

under IEA Net-Zero Emission by 2050 Scenario." Applied Energy 346 (September): 1–10. https://doi.org/10.1016/j.apenergy.2023.121400

Liao, Qiangqiang, Miaomiao Mu, Shuqi Zhao, Lizhong Zhang, Tao Jiang, Jilei Ye, Xiaowang Shen, and Guoding Zhou. 2017. "Performance Assessment and Classification of Retired Lithium Ion Battery from Electric Vehicles for Energy Storage." International Journal of Hydrogen Energy 42 (30): 18817–23. https://doi.org/10.1016/j.ijhydene.2017.06.043

Maine Climate Council. 2020. "Maine Won't Wait." Accessed August 1, 2024. https://www.maine.gov/climateplan/sites/maine.gov.climateplan/files/inline-files/MaineWontWait_December2020_printable_12.1.20.pdf

Maisch, Marija. 2024. "Sodium-Ion Batteries: A Viable Alternative to Lithium?" PV Magazine, March 22, 2024. https://www.pv-magazine.com/2024/03/22/sodium-ion-batteries-a-viable-alternative-to-lithium/

Maryland DOE (Department of the Environment). 2023. "Maryland's Climate Pollution Reduction Plan." Accessed August 1, 2024. https://mde.maryland.gov/programs/air/ClimateChange/Maryland%20Climate%20Reduction%20Plan/Maryland%27s%20Climate%20Pollution%20Reduction%20Plan%20-%20Final%20-%20Dec%2028%202023.pdf

Moody, Joanna, Elizabeth Farr, Marisa Papagelis, and David R. Keith. 2021. "The Value of Car Ownership and Use in the United States." Nature Sustainability 4 (9): 769–74. https://doi.org/10.1038/s41893-021-00731-5

Moravec, Miguel, Jackie Lombardi, Bryn Grunwald, Ryan Warsing, and Drew Veysey. 2024. "Smarter MODES Calculator: Smarter Mobility Options for Decarbonization, Equity, and Safety." Accessed July 31, 2024. https://rmi.org/insight/smarter-modes-calculator-smarter-mobility-options-for-decarbonization-equity-and-safety/

Murdock, Beth E., Kathryn E. Toghill, and Nuria Tapia-Ruiz. 2021. "A Perspective on the Sustainability of Cathode Materials Used in Lithium-Ion Batteries." Advanced Energy Materials 11: 2102028. https://doi.org/10.1002/aenm.202102028

Najman, Liz. 2024. "How Long Do EV Batteries Last?" Recurrent, May 24, 2024. https://www.recurrentauto.com/research/how-long-do-ev-batteries-last

O'Connell, Adrian, Nikita Pavlenko, Georg Bieker, and Stephanie Searle. 2023. "A Comparison of the Life Cycle Greenhouse Gas Emissions of European Heavy Duty Vehicles and Fuels." Accessed October 10, 2024. https://theicct.org/publication/lca-ghg-emissions-hdv-fuels-europe-feb23/

Owen, John R., Deanna Kemp, Alex M. Lechner, Jill Harris, Ruilian Zhang, and Éléonore Lèbre. 2023. "Energy Transition Minerals and Their Intersection with Land-Connected Peoples." Nature Sustainability 6 (2): 203–11. https://doi.org/10.1038/s41893-022-00994-6

Pinto de Moura, Maria Cecilia. 2024. "Fossil Fuels Must Go: Re-Inventing US Transportation." The Equation (blog). July 1. https://blog.ucsusa.org/cecilia-moura/fossil-fuels-must-go-re-inventing-us-transportation/

QuantumScape. 2024. "Delivering on the Promise Of Solid-State Technology." Accessed October 10, 2024. https://www.quantumscape.com/technology/

Reichmuth, David, Jessica Dunn, and Don Anair. 2022. "Driving Cleaner Electric Cars and Pickups Beat Gasoline on Lifetime Global Warming Emissions." Accessed October 10, 2024. www.ucsusa.org/resources/driving-cleaner

RioFrancos, Thea, Alissa Kendall, Kristi Dayemo, Matthew Haugen, Kura McDonald, Batul Hassan, Margaret Slattery, and Xan Lillehei. 2023. "Achieving Zero Emissions with More Mobility and Less Mining." Accessed October 10, 2024. https://www.climateandcommunity.org/more-mobility-less-mining

S&P. 2024. "Heavy and Medium Duty Electric Vehicle Data." Accessed July 25, 2024. https://www.spglobal.com/en/products/data-analytics

Sabouri, Sadegh, Guang Tian, Reid Ewing, Keunhyun Park, and William Greene. 2021. "The Built Environment and Vehicle Ownership Modeling: Evidence from 32 Diverse Regions in the US." Journal of Transport Geography 93 (May): 103073. https://doi.org/10.1016/J.JTRANGEO.2021.103073

Sen, Arijit, Josh Miller, Gabriel Hillman Alvarez, and Patricia Ferrini Rodrigues. 2023. “Vision 2050: Strategies to Align Global Road Transportation with Well Below 2°C.” Accessed October 10, 2024. https://theicct.org/publication/vision-2050-strategies-to-reduce-gap-for-global-road-transport-nov23/#:~:text=The%20strategies%20assessed%20in%20this,new%20light%2Dduty%20vehicles%3B%20further

Shen, Chang, Peter Slowik, and Andrew Beach. 2024. “Investigation of the US Battery Supply Chain and Its Impact on Electric Vehicle Costs Through 2032.” Accessed October 10, 2024. https://theicct.org/publication/investigating-us-battery-supply-chain-impact-on-ev-costs-through-2032-feb24/

Shen, Kevin, Steven Higashide, and David Cooke. 2024. “Equitable Mobility (UCS REPORT PLACEHOLDER).”

Silberg, Gary, Tom Mayor, Todd Dubner, Bala Lakshman, Yoshi Suganuma, Nehal Doshi, and Jono Anderson. 2020. “Automotive’s New Reality: Fewer Trips, Fewer Miles, Fewer Cars?” Accessed October 10, 2024. https://assets.kpmg.com/content/dam/kpmg/br/pdf/2020/09/automotives-new-reality.pdf

Sun, Xin, Minggao Ouyang, and Han Hao. 2022. “Surging Lithium Price Will Not Impede the Electric Vehicle Boom.” Joule 6 (February): 1727–42. https://doi.org/10.1039/d1ee03749h

UN (United Nations). 2007. “United Nations Declaration on the Rights of Indigenous Peoples United Nations.” Accessed October 10, 2024. /https://www.un.org/development/desa/indigenouspeoples/wp-content/uploads/sites/19/2018/11/UNDRIP_E_web.pdf

Walter, Daan, Will Atkinson, Sudeshna Mohanty, Kingsmill Bond, Chiara Gulli, and Amory Lovins. 2024. “The Battery Mineral Loop: The Path from Extraction to Circularity.” Accessed October 10, 2024. https://rmi.org/insight/the-battery-mineral-loop/

Walter, Daan, Kingsmill Bond, Sam Butler-Sloss, Laurens Speelman, Yuki Numata, and Will Atkinson. 2023. “X-Change: Batteries.” Accessed October 10, 2024. /https://rmi.org/wp-content/uploads/dlm_uploads/2023/12/xchange_batteries_the_battery_domino_effect.pdf

Washington State Legislature. 2024. RCW 47.01.440. https://app.leg.wa.gov/RCW/default.aspx?cite=47.01.440&pdf=true

Xu, Chengjian, Qiang Dai, Linda Gaines, Mingming Hu, Arnold Tukker, and Bernhard Steubing. 2020. “Future Material Demand for Automotive Lithium-Based Batteries.” Communications Materials 1 (99): 1–10. https://doi.org/10.1038/s43246-020-00095-x

Yao, Yonglin, Meiying Zhu, Zhuo Zhao, Bihai Tong, Youqi Fan, and Zhongsheng Hua. 2018. “Hydrometallurgical Processes for Recycling Spent Lithium-Ion Batteries: A Critical Review.” ACS Sustainable Chemistry and Engineering 6 (11): 13611–27. https://doi.org/10.1021/acssuschemeng.8b03545

https://doi.org/10.47923/2024.15617