Achieving Zero Emissions with More Mobility and Less Mining

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The **Climate and Community Project (CCP)** works to connect the demands of the climate justice movement to the policy development process. We aim to do this by developing new, investment-forward public policy proposals under the framework of the Decade of the Green New Deal that target the intersection of climate justice and the built environment. We support efforts to address the climate emergency at the scale, scope, and pace needed to confront our overlapping crises.

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CONTENTS

GLOSSARY

Active transit: Use of walking, bicycling, or similar as a mode of transportation.

Battery chemistry: A combination of materials that make electron sharing possible between the anode and cathode. Common battery chemistries include:

- Lithium phosphate (LFP)
- Lithium manganese oxide (LMO)
- Lithium titanate (LTO)
- Nickel manganese cobalt (NMC)
- Nickel cobalt aluminum Oxide (NCA)

Battery capacity: The total amount of energy generated by chemical reactions and stored in the battery, typically expressed in kWh for vehicle batteries.

Car fleet/vehicle stock (Vst): Quantity of in-use private passenger vehicles.

"Critical minerals": "Criticality" is generally defined in terms of two elements: (1) economic importance and (2) susceptibility to supply disruptions. In 2020, lithium was officially added to the US government's list of "critical minerals," with similar moves made in the European Union, United Kingdom, and China. Throughout the report, we use scare quotes to refer to the physical metals, because the term originates in relation to national security and war efforts, and it retains a militaristic association with supply chain control and dominance.

Electric battery bus (e-bus): A bus powered by battery-electric propulsion.

Electric vehicle (EV): An umbrella term that refers to any vehicle (passenger vehicle, bus, truck, etc.) that uses only electric propulsion and contains at least one battery. For the purposes of this report, EV refers to battery-electric personal vehicles.

Internal combustion engine (ICE): An engine that produces energy by burning fuel (for vehicles, these fuels are typically petroleum diesel and gasoline blended with 15 percent or less of ethanol).
Lithium-ion battery (LIB): A rechargeable storage system that uses lithium in its anode.

Micromobility: Refers to small vehicles used for transportation. Micromobility modes may include bicycles, scooters, skateboards/longboards, their electric equivalents, and similar modes.

Mode share: Percentage of trips done by particular types of transportation, including by private cars, public transit, walking, or bicycling.

State of health (SOH): An indicator of battery health, reported as a percentage of how much energy the battery can store compared to how much energy the battery could store when it was first produced.

EXECUTIVE SUMMARY

> "Reducing demand for lithium by increasing the lithium efficiency of the transportation sector will be an essential strategy to improve the sector's prospects for timely decarbonization while protecting ecosystems and meeting the demands of global justice."

Transportation is the number one source of carbon emissions in the United States—making the sector crucial to decarbonize quickly to limit the climate crisis. States like New York and California banned the sale of gas cars by 2035, and the 2022 Inflation Reduction Act made major federal investments in electrifying transportation. As a result, US consumers are embracing electric vehicles (EVs), with over half of the nation's car sales predicted to be electric by 2030.[1] This is a critical juncture. Decisions made now will affect the speed of decarbonization and the mobility of millions. Zero-emissions transportation will also see the transformation of global supply chains, with implications for climate, environmental, and Indigenous justice beyond US borders.

A crucial aspect of electrified transportation is new demand for metals, and specifically the most nonreplaceable metal for EV batteries—lithium. If today's demand for EVs is projected to 2050, the lithium requirements of the US EV market alone would require triple the amount of lithium currently produced for the entire global market. This boom in demand would be met by the expansion of mining.

Large-scale mining entails social and environmental harm, in many cases irreversibly damaging landscapes without the consent of affected communities. As societies undertake the urgent and transformative task of building new, zero-emissions energy systems, some level of mining is necessary. But the volume of extraction is not a given. Neither is where mining takes place, who bears the social and environmental burdens, or how mining is governed.

This report finds that the United States can achieve zero-emissions transportation while limiting the amount of lithium mining necessary by reducing the car dependence of the transportation system, decreasing the size of EV batteries, and maximizing lithium recycling. Reordering the US transportation system through policy and spending shifts to prioritize public and active transit while reducing car dependency can also ensure transit equity, protect ecosystems, respect Indigenous rights, and meet the demands of global justice.

We designed a novel material flow analysis paired with socioeconomic pathway modeling to determine possible scenarios for the decarbonization of personal transportation in the United States. We focus on US passenger transportation. The transportation sector is the number one source of US emissions, and the only

1 Benchmark Mineral Intelligence, "More than 300 New Mines Required to Meet Battery Demand by 2035," September 6, 2022, https://www.benchmarkminerals.com/membership/more-than-300-new-mines-required-to-meet-battery-demand-by-2035/.

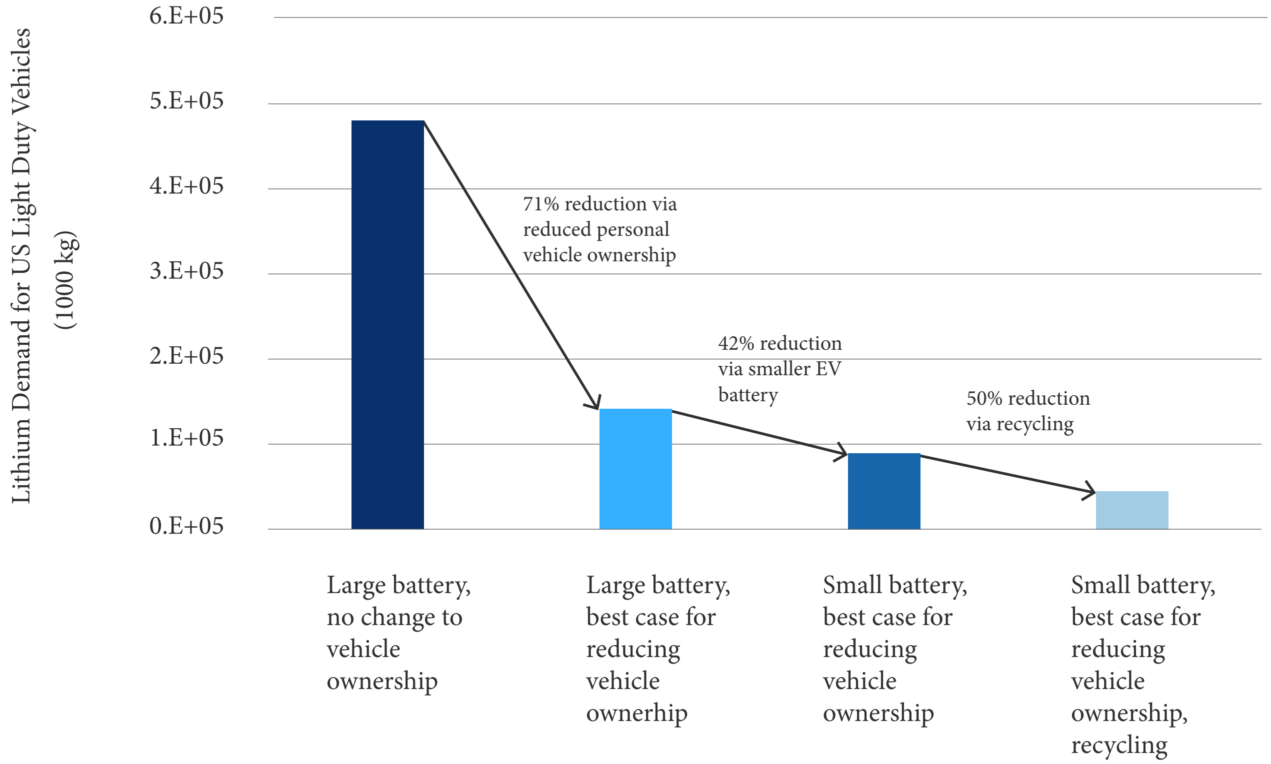

Figure 1. Annual Lithium Demand Reduction for US Passenger Transport as a Function of Best and Worst Cases for Future Vehicle Ownership Rates, Vehicle Design, and Recycling in 2050. Note that reductions scale proportionally; for example, recycling reduces lithium demand by 50% for any scenario combination chosen.

sector in which emissions are still steadily rising; within transportation, most emissions come from light-duty vehicles.[2] We compare the lithium requirements of four pathways to zero-emissions personal transportation: an electrified continuation of the current US car-dependent status quo, and three scenarios that adopt increasingly ambitious policies to support public and active transportation and reduced car dependency.

Results

- Compared to a decarbonization scenario that maintains US vehicle ownership rates, scenarios that reduce car dependency, and therefore use and ownership, and limit EV battery size can lower the demand for lithium between 18 and 66 percent.
- Even if the car-centricity of the US transportation system continues, limiting the size of EV batteries can cut lithium demand by as much as 42 percent.

Policies that increase and incentivize active and mass transit, lower the size of EVs and their batteries, and responsibly source their minerals will support a rapid and equitable transportation transition by reducing the battery demand of a zero-carbon transportation future.

The benefits of this ambitious approach go beyond the transportation sector:

- **Centering the frontlines of lithium mining**: Too often, transit justice, environmental justice, and Indigenous justice are pitted against each other in conversations about the decarbonization of the US transportation system. This report attempts to bring the many shared goals of these movements into conversation. We examine four cases of lithium mining: Argentina, Chile, the United States, and Portugal. In each of these cases, proposed or ongoing lithium mining has concerning implications for drought intensity, ecosystem biodiversity, and Indigenous

2 "Greenhouse Gas Inventory Data Explorer," United States Environmental Protection Agency, accessed November 22, 2022, https://cfpub.epa.gov/ghgdata/inventoryexplorer/#allsectors/allsectors/allgas/select/all; Jon Sindreu, "In the Green Transition, Transportation Is the Next Big Baddie," Wall Street Journal, December 23, 2019, https://www.wsj.com/articles/in-the-green-transition-transportation-is-the-next-big-baddie-11577119404.

sovereignty and/or community participation in projects that threaten cultural landscapes and economic livelihoods. Reducing the lithium intensity of electrified transportation would in turn mitigate a key driver of these harms.

- **Reducing geopolitical tensions**: With new demand for lithium and other energy transition–related metals comes new mining, a global industry notorious for its environmental destruction and concerning record of human rights abuses and violence. In addition to these local harms, so-called "critical minerals" are a site of geopolitical tension. Lithium supply chains span the world from Latin America to China to Australia, with new extraction being planned in Europe, Canada, the United States, and beyond. The massive uptick in demand is already producing supply bottlenecks for EV production, slowing EV uptake, calling into question their affordability, and stoking geopolitical tension as nations compete for access to lithium deposits. Lowering the amount of lithium necessary for decarbonization will limit bottlenecks and lower the potential of environmental degradation, injustice, and conflicts associated with mining.
- **Achieving climate targets**: Mining-related harms and looming supply constraints are two reasons to reduce the material intensity of electrified transportation. In addition, existing research has found that expanding mass transit hastens decarbonization. Vehicle electrification, declines in car usage and ownership, and reductions in the size and weight of personal vehicles (to increase their energy efficiency) are necessary steps that must be pursued in combination to remain within a sectoral carbon budget consistent with limiting to 1.5-2°C of warming.[3] The speed of decarbonization of light-duty vehicles is limited by the turnover of the existing vehicle fleet and its replacement with EVs, as well as the decarbonization of the electricity grid. Producing EVs and building and maintaining roads, highways, and parking lots are energy- and emissions-intensive processes with high levels of embodied carbon. Electrification of the US transportation system will massively increase the demand for electricity while the transition to a decarbonized electricity grid is still underway, increasing the magnitude of that challenge.[4] Public transit and active transit tend to be dramatically more energy-efficient methods of allowing people to move around; increasing the shares of travel happening by these modes will hasten decarbonization.
- **Designing safer communities**: Increasing mass and active transit as well as keeping passenger vehicles smaller makes for safer communities. Reducing the size of passenger vehicles also can make the roads far safer because smaller cars have fewer and less severe crashes. Making bus routes, metros, and electric bikes faster, safer, and more convenient will disproportionately support low-income and non-white community members—who are more likely to live near high-traffic areas and bear the environmental health burdens of relatively poorer air quality compared to higher-income and white counterparts.

Major investments to shift away from US car dependency would have benefits spanning from the frontlines of mining, which would see reduced social and environmental harms, to densified metropolitan areas throughout the country, which would experience myriad benefits from improved air quality to pedestrian safety. Ultimately, climate, transit, and Indigenous justice can be aligned. Doing so requires an ambitious rethinking of the energy transition that emphasizes benefits for communities and ecosystems most impacted by the climate crisis. In order to achieve a just future, the movement for climate justice must present a united front against profit-driven extraction.

3 A. Milovanoff, I. D. Posen, and H. L. MacLean, "Electrification of Light-Duty Vehicle Fleet Alone Will Not Meet Mitigation Targets," Nature Climate Change 10 (2020): 1102–1107, https://doi.org/10.1038/s41558-020-00921-7; Hill et al., "The Role of Electric Vehicles in Near-Term Mitigation Pathways and Achieving the UK's Carbon Budget"; Jalel Sager, Joshua S. Apte, Derek M. Lemoine, and Daniel M Kammen, "Reduce Growth Rate of Light-Duty Vehicle Travel to Meet 2050 Global Climate Goals," Environmental Research Letters 6, no. 2 (2011): 024018, https://doi.org/10.1088/1748-9326/6/2/024018; Fulton et al., "The Compact City Scenario - Electrified: The Only Way to 1.5°C."

4 Milovanoff et al., "Electrification of Light-Duty Vehicle Fleet Alone Will Not Meet Mitigation Targets," write: "We show that betting solely on EVs to remain within suitable sectoral CO2 emission budgets for the US LDV fleet would . . . [add] half of national electricity demand."

INTRODUCTION

A habitable earth, for humans and nature alike, necessitates the comprehensive decarbonization of all realms of social life.[5] The climate crisis intensifies with each year, and time is running out to transition energy systems and energy-intensive sectors off of fossil fuels and stay within relatively safe levels of warming. But as our analysis of the transportation sector shows, there is more than one pathway to decarbonization. The singular goal can be to reduce greenhouse gas emissions to zero, while preserving the status quo of car dependence—or, the energy transition can be used as an opportunity to address the root causes of the climate and environmental crisis, and the social inequalities entangled with both.

The United States is the source of the most historic emissions and currently one of the world's highest per capita emitters. It has an obligation to do its "fair share" of emissions reduction.[6] Doing so in a way that lifts up communities within US borders and beyond them means scrutinizing the patterns of production and consumption that have rendered the United States such a carbon-intensive and unequal society.[7]

In the United States, the transportation sector is arguably the most important sector to not only decarbonize but to fundamentally rethink and transform in the process. The transportation sector is the leading source of US greenhouse gas emissions, accounting for 28 percent of the total.[8] It is the only major sector in which emissions are still rising, apart from a temporary drop in 2020 during the peak of COVID-19 disruptions.[9] The ground transportation sector also produces—both directly and indirectly—myriad other forms of social and environmental injustices, including air pollution from exhaust, tire, and brake dust and other particulates; deaths and injury from car crashes; social isolation; high housing costs; financial burdens on households and governments; noise pollution; racial segregation; and more. These harms are disproportionately borne by poor, Black, and Brown communities.[10]

The transportation system in the United States has been constructed through public policies and spending priorities that have engineered car dependency, reconfiguring the built environment to prioritize the movement and storage of millions of private vehicles. Meanwhile, mainstream US climate policy—like the Inflation Reduction Act of 2022—has, thus far, largely doubled down on car dependency.[11] Recent climate investments have focused on vehicle technology solutions like replacing internal combustion engine (ICE) vehicles with battery electric vehicles (EVs), with relatively little action to fund the electrification and expansion of mass transit or support people who walk or bike.[12]

Broadly speaking, there are two ways to decrease transportation emissions: replacing the ICE vehicle fleet with EVs, or reducing the total volume of vehicles on the road. The current dominant strategy for the sector—replacing ICE vehicles with EVs without decreasing car ownership and use—is likely incompatible with keeping global warming below 1.5 degrees.[13] To combat the climate

5 IPCC, "Climate Change 2022: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama (eds.)] (Cambridge and New York: Cambridge University Press), 2022, http://doi:10.1017/9781009325844.

6 "The US Climate Fair Share," US Climate Fair Share Position Statement, accessed November 21, 2022, https://usfairshare.org/.

7 Peter Newell and Dustin Mulvaney, "The Political Economy of the 'Just Transition,'" Geographical Journal 179, no. 2 (2013): 132–40, https://doi.org/10.1111/geoj.12008; Patrick Bond, Politics of Climate Justice: Paralysis Above, Movement Below (Scottsville, South Africa: University of KwaZulu-Natal Press, 2012); Jason Henderson, "EVs Are Not the Answer: A Mobility Justice Critique of Electric Vehicle Transitions," Annals of the American Association of Geographers 100, no. 6 (2020): 1993–2010, https://doi.org/10.1080/24694452.2020.1744422.

8 US Environmental Protection Agency, "Sources of Greenhouse Gas Emissions," https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

9 US Environmental Protection Agency, "Sources of Greenhouse Gas Emissions."

10 Angie Schmitt, Right of Way: Race, Class, and the Silent Epidemic of Pedestrian Deaths in America (Washington, D.C.: Island Press, 2020); Jessie Singer, There Are No Accidents: The Deadly Rise of Injury and Disaster-Who Profits and Who Pays the Price (New York: Simon & Schuster, 2022); Hiroko Tabuchi and Nadja Popovich, "People of Color Breathe More Hazardous Air. The Sources Are Everywhere," New York Times, April 28, 2021, https://www.nytimes.com/2021/04/28/climate/air-pollution-minorities.html.

11 Yonah Freemark, "What the Inflation Reduction Act Did, and Didn't Do, for Sustainable Transportation," Urban Institute, September 15, 2022, https://www.urban.org/urban-wire/what-inflation-reduction-act-did-and-didnt-do-sustainable-transportation.

12 For example, the 2021 Infrastructure, Investment, and Jobs Act included $1.6 billion for the expansion of transit e-buses, $7.5 billion for the expansion of EV charging infrastructure, and $350 billion in federal highway program funding.

13 Milovanoff et al., "Electrification of Light-Duty Vehicle Fleet Alone Will

crisis, electrification of private vehicles must be paired with the creation of a transportation system that allows and encourages people to meet their everyday needs without requiring access to a car. As existing research shows, reducing car dependency hastens decarbonization, thus addressing the key demand of climate justice.[14]

This report shows that reducing car dependency aligns with global justice for another reason: it results in less demand for lithium, thus safeguarding vulnerable ecosystems from degradation, reducing pressure on water supplies, and protecting communities from the conflict and human rights abuses associated with the mining sector. Indeed, the mineral supply chains of EVs reveals some of the most glaring injustices of the prevailing approach to the energy transition. The production of EVs begins with prospecting, exploration, and extraction of so-called "critical minerals" like lithium. Throughout the report, we place "critical minerals" in scare quotes because the term originates in relation to national security and war efforts, and it retains a militaristic association with supply chain control and dominance. The government and corporate goal of supply chain dominance is often marshaled to justify a rapid expansion of mining, running roughshod over human rights and environmental regulations.

Under prevailing technologies, lithium is an essential ingredient in the batteries that power EVs, as well as other consumer electronics and forms of electric mobility such as e-buses, e-trucks, and e-bikes. Lithium mining—currently concentrated in Australia, Chile, China, and Argentina—is, like all mining, environmentally and socially harmful. Globally, mining is the economic sector most associated with local conflicts between environmental defenders and corporations, and in particular with violent encounters in which environmental defenders are assassinated.[15] It is also worth noting that Latin America—the location of two of our case studies, Chile and Argentina—is consistently the deadliest region in the world for environmental defenders. [16]In addition, mining constitutes a major threat to tropical forests—and thus to biodiversity, Indigenous territory, and the planet's most crucial carbon sinks.[17] Lastly, as our case studies will demonstrate, existing and planned lithium mines overlap with zones of severe water stress—and mining is often a water-intensive and water-contaminating process.

These facts raise fundamental questions. How can the transition to renewable energy avoid creating new sacrifice zones, where ecosystems are disrupted, rights violated, and social conflict triggered under the banner of fighting the climate crisis? What is the most globally just pathway to decarbonizing the US transportation sector, the number one source of US emissions?[18]

This report begins to provide an answer. Combining qualitative and quantitative methodologies, it is the first report to model multiple pathways to decarbonize the US transportation sector with the goal of comparing their respective lithium intensities. Complementing this model is a rigorous analysis of the impacts of current and projected lithium mining, alternatives to mining including recycling, and detailed descriptions of various possible transportation futures, ranging from the electrification of the car-dependent status quo, to an ambitious, transformative vision of increased mass transit, cycling, and walking; reduced private vehicle ownership; and denser cities and suburbs. Given that the construction of car dependency in the United States was inextricable from the creation of highly racialized urban geographies—with highway construction, urban renewal programs, and massive, racially exclusive subsidies for car-oriented suburban development underpinning continuing segregation by race and class—reversing these trends will also entail an enormous opportunity to begin to rectify major social harms, although such steps would also have to be supplemented with other policies explicitly oriented toward advancing social equity.

Projections show skyrocketing demand for "critical minerals" like lithium. While these projections can feel like

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Not Meet Mitigation Targets"; Institute for Transportation and Development Policy, "To Combat Climate Change, Electrification Needs Compact Cities for Full Impact—Institute for Transportation and Development Policy," Promoting Sustainable and Equitable Transportation Worldwide, December 10, 2021, https://www.itdp.org/2021/12/09/why-electric-vehicles-are-not-a-climate-change-silver-bullet/; Sager et al., "Reduce Growth Rate of Light-Duty Vehicle Travel to Meet 2050 Global Climate Goals."

14 Freemark, "What the Inflation Reduction Act Did, and Didn't Do"; Milovanoff et al., "Electrification of Light-Duty Vehicle Fleet Alone Will Not Meet Mitigation Targets."

15 Arnim Scheidel, Daniela Del Bene, Juan Liu, Grettel Navas, Sara Mingorría, Federico Demaria, Sofía Avila, et al., "Environmental Conflicts and Defenders: A Global Overview," Global Environmental Change 63 (2020): 102104.

16 Decade of Defiance," Global Witness, accessed November 22, 2022, https://www.globalwitness.org/en/campaigns/environmental-activists/decade-defiance/.

17 Stefan Giljum, Victor Maus, Nikolas Kuschnig, Sebastian Luckeneder, Michael Tost, Laura J. Sonter, and Anthony J. Bebbington, "A Pantropical Assessment of Deforestation Caused by Industrial Mining," Proceedings of the National Academy of Sciences 119, no. 38 (2022): e2118273119.

18 US Environmental Protection Agency, "Sources of Greenhouse Gas Emissions."

abstractions, they paint a concerning future with real-world implications. Whether accurate or not, predictions of high demand and tight supplies have concrete consequences: they encourage a "race" to explore and extract, wherein government leaders and corporate executives prioritize supply chain dominance over socio-environmental governance. Some of the most alarming recent forecasts indicate that an almost 200 percent increase in the number of lithium mines will be needed by 2035 to meet expected demand for EVs.[19] If built, each of these mines would entail ecological and safety risks—including water contamination, massive quantities of physical waste, and endangered biodiversity—as well as potentially harming cultural landscapes and undermining other land uses or place-dependent livelihoods. Given prevailing practices by the mining industry, it is unlikely that Indigenous or other communities would be meaningfully consulted or asked for their Free, Prior and Informed Consent, or that the very basics of transparent, objective information would be provided to affected residents as they contemplate a massive change in their immediate environment. Meanwhile, bottlenecks in the supply of "critical minerals" are already delaying the tight timeline for decarbonization of the sector.[20] **Reducing demand for lithium by increasing the lithium efficiency of the transportation sector will be an essential strategy to improve the sector's prospects for timely decarbonization while protecting ecosystems and meeting the demands of global justice.**

At the same time, the growing concern that demand for lithium will outpace supply is stoking geopolitical tensions and incentivizing corporate control across the supply chain. Governments in the United States, Canada, and Europe are increasingly invoking national security claims for "critical minerals," using fiscal and regulatory tools to incentivize the production of lithium and other transition-related extractive sectors in the United States.[21] Concretely, this has taken the form of direct investments, tax breaks, loans, research and development allocations, financial de-risking, and fast tracking of licenses and permits. Such policies are evident in the Infrastructure Investment and Jobs Act (2021), the Inflation Reduction Act (2022), the European Union (EU)'s Raw Material Alliance, and actions taken by specific agencies and institutions, such as the Department of Energy, the European Investment Bank, the European Institute of Innovation and Technology, and more.

On the ground, this has resulted in a push for new lithium mining projects in the Global North (the US state of Nevada has upwards of 50 lithium projects currently in development[22]), alongside the expansion and intensification of mining in preexisting top global producers such as Chile and Argentina. This mining-intensive approach to decarbonizing transportation, hinging on the mass production and deployment of individual passenger EVs, is now the primary driver of demand for lithium—and thus for new lithium mines.[23]

In this context, it is clear that models of lithium demand, which estimate the lithium requirements of zero-emissions transportation sectors dominated by passenger EVs, do not just reflect the future but play a role in shaping it. Armed with the forecasts of the International Energy Agency, Bloomberg New Energy Finance, Benchmark Minerals, and the World Bank,[24] policymakers and corporate representatives make the case for fast-tracking permitting, gutting environmental regulation, and directly subsidizing the mining industry. Meanwhile, lithium companies see record profits, buoyed stock prices, and strong competition among end-use buyers for their products.[25]

19 Benchmark Mineral Intelligence, "More than 300 New Mines Required to Meet Battery Demand by 2035."

20 Tae-Yoon Kim, "Critical Minerals Threaten a Decades-Long Trend of Cost Declines for Clean Energy Technologies – Analysis," International Energy Agency, May 18, 2022, https://www.iea.org/commentaries/critical-minerals-threaten-a-decades-long-trend-of-cost-declines-for-clean-energy-technologies.

21 Sophia Kalantzakos, "The Race for Critical Minerals in an Era of Geopolitical Realignments," The International Spectator 55, no. 3 (2020): 1–16; Thea Riofrancos, "The Security–Sustainability Nexus: Lithium Onshoring in the Global North," Global Environmental Politics (2022): 1–22; Daniel Scholten, Morgan Bazilian, Indra Overland, and Kirsten Westphal, "The Geopolitics of Renewables: New Board, New Game," Energy Policy 138 (2020): 111059.

22 For this figure, see the map maintained by Patrick Donnelly, Great Basin Director for the Center for Biological Diversity: https://www.google.com/maps/d/u/0/viewer?mid=1kq8TRUSMR97kg-XQ22kdQpE4lUT0Rj49&ll=38.27493251229278%2C-111.5045488&z=6.

23 Colin McKerracher, "EV Outlook 2022," BloombergNEF, June 2022, https://about.bnef.com/electric-vehicle-outlook/.

24 In contrast to these other entities, Goldman Sachs has consistently predicted supply/demand balance, and most recently gone as far as to predict oversupply. In our discussion of forecasting below, we will address these large disparities in projections. See Kerry Sun, "Lithium Stocks Smashed after Bearish Notes from Goldman Sachs and Credit Suisse," MarketIndex.com.au, November 15, 2022, https://www.marketindex.com.au/news/lithium-stocks-smashed-after-bearish-notes-from-goldman-sachs-and-credit.

25 Annie Lee, "China's Lithium Giants Report Record Earnings as Prices Soar in Supply Shortage," Bloomberg, August 31, 2022, https://www.bloomberg.com/news/articles/2022-08-31/china-s-lithium-giants-notch-earnings-records-on-supply-crunch; B. A. McKenna, "Albemarle Earnings Reflect Continued Strong Lithium Demand and Prices," Motley Fool, August 8, 2022, https://www.fool.com/investing/2022/08/08/alb-stock-alb-earnings-albemarle-stock-earnings/; "Chile's SQM Profit Soars on High Lithium Prices," Reuters, May 19, 2022, https://www.reuters.com/business/energy/

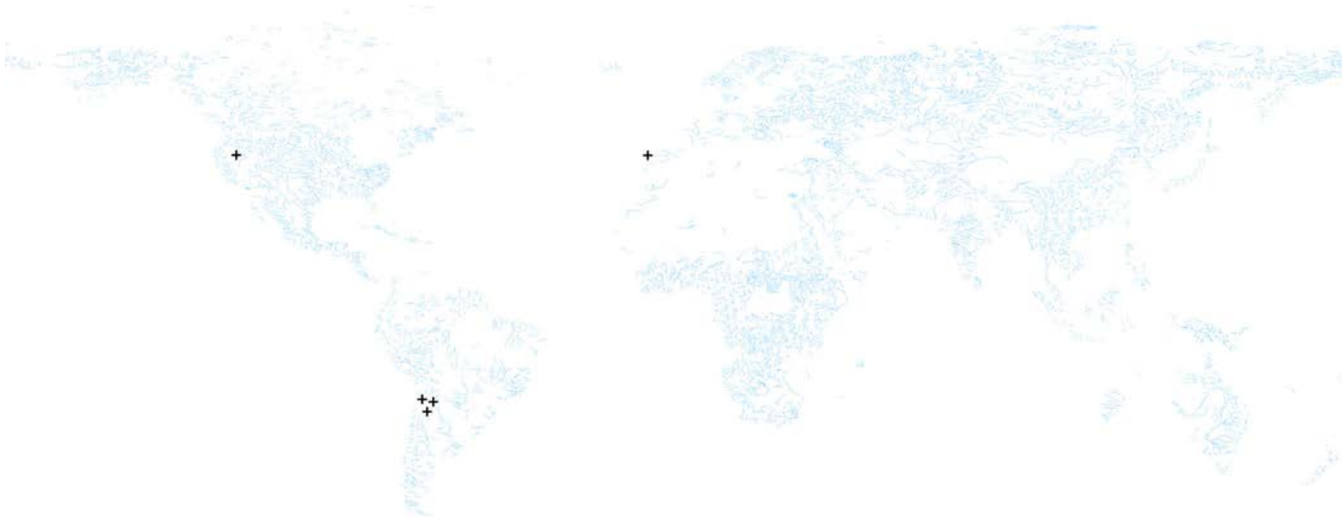

Figure 2: Global case studies.

It is critical, therefore, to offer a different vision of the future. The authors of this report understand that some level of mining is necessary, as societies undertake the historic task of building a new energy system using technologies and infrastructures that are produced with mineral inputs. **We argue throughout this report that the volume of extraction is not a given. Neither is it a given where that extraction takes place, under what circumstances, the degree of the environmental and social impacts, or how mining is governed. As a corollary, we show that one of the most important levers available to reduce mining-related harm is at the other end of the supply chain: the built environment and technologies of electrified transportation.** The more the United States can shape the future of zero-emissions transportation with an eye to reducing its lithium intensity, the more that future will be aligned with global justice. A transportation future that minimizes its reliance on supply chains that are sites of geopolitical conflict and corporate power will also reduce vulnerability to political and market instability.[26]

In the sections that follow, this report provides basic context for the state of lithium and its supply chains, including the element's physical properties, geographic distribution, and importance for lithium-ion batteries (LIBs) in EVs. It gives an overview of the social and ecological effects of rock and brine lithium mining, illustrated by four case studies—in the United States, Portugal, Chile, and Argentina—and reviews existing models for projected future lithium extraction required for transportation decarbonization.

chiles-sqm-net-rises-12-fold-high-lithium-prices-2022-05-19/.

26 For analysis of "critical minerals" as a new flashpoint in geopolitical conflict, see Kalantzakos, "The Race for Critical Minerals in an Era of Geopolitical Realignments."

Next, the report identifies four possible decarbonized mobility scenarios, each representing a zero-emissions transportation future.[27] Beyond that commonality, they vary along several key dimensions, including transportation mode shares, urban area[28] density, and vehicle ownership rates. Each of these dimensions carries implications for lithium intensity. In concrete terms, Scenario 1 preserves the status quo of US car dependency and spatial sprawl, but replaces all ICE vehicles with EVs. In contrast, Scenario 4 replaces all ICE vehicles with EVs, but also reduces the percentage of trips taken in passenger cars while also reducing overall personal vehicle ownership; increases the trips taken via mass transit, cycling, and walking; and sees densified metro areas better able to support more public and active transit for more trips.[29]

Specifically, mode shares reflect the achievement of ambitious goals similar to those set by cities such as Vienna that aim to intentionally decrease the level of car use in order to improve livability and sustainability. Given levels of car use are associated with lower levels of car ownership, reflecting the lower bounds of this relationship currently seen in comparable global cities; bus requirements for a given level of travel by public transport decline further.

27 The parameters were determined from a survey of global data on transportation systems, which is presented alongside the decarbonized mobility scenarios.

28 "Urban areas" in this report refers to the areas as defined by the US Census Bureau, which include the developed land area, including both urban centers and lower-density or suburban peripheries. See "Urban and Rural," Census.gov, US Census Bureau, October 3, 2022, https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-rural.html.

29 We look primarily at European cities for reasons of data completeness and comparability to US cities. This is discussed further in the appendix.

Table 1: Decarbonized Mobility Scenarios

Scenario	Description
Scenario 1	Current systems of private transportation and land use remain unchanged. Rates of usage and ownership of cars remain constant, and the number of vehicles required changes only with population. The public transportation system similarly changes only to reflect population growth
Scenario 2	More people are walking, biking, and/or taking buses or trains rather than depending on cars for the vast majority of trips. Levels of car dependence in US cities and suburbs are reduced to the equivalent of comparable EU cities. US mode shares—the proportions of public traveling by private vehicle and public and active transit—change within urban areas to reflect current averages in European urban areas, where incomes and density are relatively comparable but where public policy and infrastructural shifts have facilitated substantial mode shift away from private vehicles in recent years.[29] The mode share in rural areas in the United States remains unchanged.
Scenario 3	The mode shift in Scenario 2 is supplemented by changes in land use and other policy and norm changes. Cities are denser, with built environments more supportive of active and public transit; car ownership becomes less convenient and less highly subsidized, leading to further decreased personal car ownership. More specifically, the proportion of the population in rural areas remains unchanged, but many urban areas densify modestly to levels that can support larger shares of public and active transit. Additionally, this scenario assumes policy and norm changes that decrease the level of car ownership associated with given levels of car use, again bringing this relationship in line with those seen in other, comparable global cities. Public transit also begins to reduce its lithium intensity per trip by shifting to more electrified rail rather than buses, although our modeling will show this has far smaller impact on lithium requirements than lowering car use and ownership.
Scenario 4	Similar changes to those in Scenarios 2–3 happen, but the shifts are more dramatic. Even more people are using mass transit, cycling, and walking to get where they need to go, and more people live in medium-dense urban areas in which the distances between home, work, school, and socializing are decreased. Changes in the built environment, policy, and norms further reduce the resource intensity of the transportation system. Specifically, mode shares reflect the achievement of ambitious goals similar to those set by cities such as Vienna that aim to intentionally decrease the level of car use in order to improve livability and sustainability. Given levels of car use are associated with lower levels of car ownership, reflecting the lower bounds of this relationship currently seen in comparable global cities; bus requirements for a given level of travel by public transport decline further.

A further discussion of the parameters used to establish these scenarios follows in the appendix.

The next step is to translate vehicle demands to lithium requirements. We calculate the total battery capacity demanded for each scenario using historic EV sales data, forecasts, and average battery size, then estimate the material demand based on cathode chemistry mix and the lithium intensity of EV batteries. This allows us to estimate how much lithium would be required between 2020 and 2050 under each of the four mobility scenarios. The model also considers fleet turnover models, battery sizes, warranty periods, and recycling.

The results demonstrate that changes to status quo mode share and vehicle design (i.e., battery size) significantly influence the cumulative demand for LIBs—and, therefore, the lithium required to produce them. **When comparing the lithium demand of different transportation futures with Scenario 1, there is an 18 percent, 41 percent, and 66 percent reduction for Scenarios 2, 3, and 4, respectively.** LIB size also affects lithium demand and along with vehicle efficiency determines the range an EV can travel between charging. Thus, battery size will typically shrink for smaller vehicles with shorter range. The US market has historically had disproportionately large LIBs compared to global averages; for example, in 2021 the global average EV had a battery capacity of just over 40 kWh, while the average US EV had an average battery capacity of just over 70 kWh, approximately double the capacity of a decade ago.[30] The battery requirements of the largest personal EV models on the US market are as large as 150 kWh. For reference, a typical e-bike LIB is about a half kWh or smaller.

This model explored three futures: where average US EV battery capacity is small, shrinking to 54 kWh; is medium, staying nearly static at 77 kWh; or is large, growing to 123 kWh. Cumulative lithium demand could be reduced by nearly one-third (29 percent) under Scenario 1, if average battery capacity goes from medium to small. These results suggest that reducing demand for passenger vehicles, densifying urban centers, and maintaining and reducing battery size are the most effective pathways to reducing future lithium demand. It may seem overly ambitious to propose transforming the US transportation sector, which is deeply ingrained in the national landscape of highways and parking lots, suburban sprawl and single family homes, just as it is embedded in everyday habits, cultural identities, and even notions of freedom and autonomy. But despite the challenge, it is vital to expand horizons of possibility in critical social debates around the climate crisis, the energy transition, and the rapid growth in green investment. The current car-centric approach presents its own challenges, given the deepening supply crunch and mining impacts for lithium and other "critical minerals." **In all of the scenarios modeled in this report except the most ambitious scenario, US demand for lithium far outpaces current global production of the mineral.** If today's status quo conditions are extended to 2050, US EV-driven demand for lithium alone would require three times more lithium than is currently produced for the global market—including in the EU and China, markets that are currently larger than the United States. Even if ideal conditions for recycling are met and able to drive down demand by nearly one-third, US EV-driven lithium demand will exceed global production at an unsustainable rate.

A zero-emissions transportation sector that reduces car dependency in favor of expanding mass transit, walking, and cycling paired with urban and suburban planning that permits these changes would bring countless co-benefits. These include reduced injuries and fatalities, reduced tire and brake pollution, reduced financial burdens on low-income car owners, and even reduced residential segregation by race and class, while simultaneously improving physical well-being and local economic vibrancy. The Climate and Community Project's 2022 report, "A Green New Deal for Transportation," outlined just such a vision for a green, environmentally just mobility network, with specific recommendations for public policy and programs to transform the US transportation sector.[31]

In order to achieve this future, the movement for climate justice must present a united front against profit-driven extraction that harms communities and ecosystems. Too often, communities on the frontlines of lithium extraction are pitted against climate activists fighting for decarbonization of the transportation sector. This report attempts to contribute to a unifying vision for supply chain justice that aligns climate, environmental, Indigenous, and transit justice in global terms, by reducing the mining intensity of transportation decarbonization and simultaneously benefiting communities at each node

30 Martin Placek, "Worldwide Battery Capacity in Electric Vehicles 2025," Statista, March 22, 2021, https://www.statista.com/statistics/309584/battery-capacity-estimates-for-electric-vehicles-worldwide/; "Light-Duty Electric Vehicle Sales Model," EV Volumes, EV Data Center, 2022, http://www.ev-volumes.com/datacenter/.

31 Yonah Freemark, Billy Fleming, Caitlin McCoy, Rennie Meyers, Thea Riofrancos, Xan Lillehei, and Daniel Aldana Cohen, "Toward a Green New Deal for Transportation: Establishing New Federal Investment Priorities to Build Just and Sustainable Communities," Climate and Community Project, 2022.

of the lithium supply chain. To this end, the development of the report was guided by an ongoing process of community review with partners in Nevada (the People of Red Mountain, Great Basin Resource Watch), Chile and Argentina (Observatorio Plurinacional de Salares Andinos; Fundación Ambiente y Recursos Naturales), and Portugal (Associação Unidos em Defesa de Covas do Barroso). These partners were consulted from the early stages of research development through presentations of findings in an effort to ensure that perspectives from the extractive frontiers of the lithium industry were accurately represented in the broader discussion of pathways to zero-emissions transportation.

The transportation decisions made in the United States have implications for communities and landscapes around the world, as supply chains provide the critical materials for manufacturing EVs for the US market—and also because US consumption habits constitute an aspirational goal for upwardly mobile and affluent people around the world. Just as the United States has a responsibility to cut its fair share of emissions, it also has a responsibility to reduce stress on harmful and vulnerable supply chains, and to model a different transportation future. We hope that this report plays a small role in that ambition.

“The United States has a responsibility to cut its fair share of emissions, it also has a responsibility to reduce stress on harmful and vulnerable supply chains, and to model a different transportation future.”

LITHIUM AND ELECTRIC VEHICLES

Lithium is a soft, white metal that is so reactive it naturally occurs only in compound form. It is the 33rd most common element on the planet.[32] As of 2022, global lithium resources are around 89 million metric tons, and reserves are around 22 million metric tons.[33] Geologically, lithium deposits are fairly widespread and abundant. But lithium production is highly concentrated geographically, with just four countries—Australia, Chile, China, and Argentina—accounting for more than 95 percent of global production. [34]

While lithium has myriad uses, including in psychiatric medicine, ceramics, glass, and lubricants, approximately two-thirds of lithium demand today is for rechargeable batteries. Even at presently low levels of adoption, EVs are already the largest source of this demand because they use enormous packs of LIBs that account for 30-40 percent of an EV's value and require around 1,000 times as much lithium as small consumer electronics like cell phones.[35] As the transition from ICE vehicles to EVs accelerates, this demand will surge because lithium, as the only element common to all current battery chemistries, is not substitutable for the time being.

32 H. Aral and A. Vecchio-Sadus, "Lithium: Environmental Pollution and Health Effects," Encyclopedia of Environmental Health, 2011, 499–508, https://doi.org/10.1016/b978-0-444-52272-6.00531-6.

33 The amount of existing lithium is categorized as deposits, resources, and reserves. Deposits are any found quantity of lithium, resources are deposits that are physically extractable but not yet economically viable, and reserves are resources that are physically and economically available to extract. See "Mineral Commodity Summaries 2022," U.S. Geological Survey, 2022, https://doi.org/10.3133/mcs2022.

34 "Mineral Commodity Summaries 2022."

35 See Figure 1 in Sophie Lu and James Frith, "Will the Real Lithium Demand Please Stand Up? Challenging the 1MT-by-2025 Orthodoxy," BloombergNEF, October 28, 2019, https://about.bnef.com/blog/will-the-real-lithium-demand-please-stand-up-challenging-the-1mt-by-2025-orthodoxy/; "Global Supply Chains of EV Batteries," Global Energy Review 2021, International Energy Agency, April 2021, https://iea.blob.core.windows.net/assets/d0031107-401d-4a2f-a48b-9eed19457335/GlobalEnergyReview2021.pdf; John D. Graham, John A. Rupp, and Eva Brungard, "Lithium in the Green Energy Transition: The Quest for Both Sustainability and Security," Sustainability 13, no. 20 (2021): 11274, https://doi.org/10.3390/su132011274.

Lithium-ion Battery Chemistries

Lithium is vital for rechargeable batteries because of its low weight and high conductivity. An LIB cell consists of a cathode (negative charge), an anode (positive charge), an electrolyte liquid, a separator, and a positive and a negative current collector. The lithium is stored in the cathode and the anode. When the battery is charging, negatively charged lithium ions travel from the cathode to the anode and the negative current collector through the separator via the electrolyte; when the battery is in use (i.e., discharging), this process goes in reverse. An EV battery combines thousands of these cells in one pack.

There are a variety of LIB chemistries using different materials in the cathode with lithium, the most common being nickel with cobalt and manganese.[36] Alternative battery technologies that do not use lithium, like sodium-ion batteries, are being researched but are not yet viable or proven at a commercial scale, so lithium-ion will be the sole technology for EVs in the foreseeable future.[37]

Existing Projections of EV Sales and Battery Mineral Demand

In 2021, global lithium production was estimated at just over 100,000 metric tons and consumption at 93,000 metric tons.[38] Both production and consumption have increased significantly in recent years alongside identification of new deposits, with subsets that are technically and economically feasible to exploit.

Despite ongoing discoveries, most forecasters predict a near- to medium-term gap between market supplies and demand, resulting in a supply crunch in the next 5 to 10 years—a critical period during which rapid decarbonization must take place in order to avert even more catastrophic global warming. This imbalance between supply and demand is reflected in high prices for battery-grade lithium, which by September 2022 were nearly

36 "Global Supply Chains of EV Batteries," Global Energy Review 2022, International Energy Agency, July 2022, https://iea.blob.core.windows.net/assets/4eb8c252-76b1-4710-8f5e-867e751c8dda/GlobalSupplyChainsofEVBatteries.pdf.

37 Alex Scott, "Sodium Comes to the Battery World," Chemical & Engineering News, May 24, 2022, https://cen.acs.org/business/inorganic-chemicals/Sodium-comes-battery-world/100/i19.

38 "Mineral Commodity Summaries 2022."

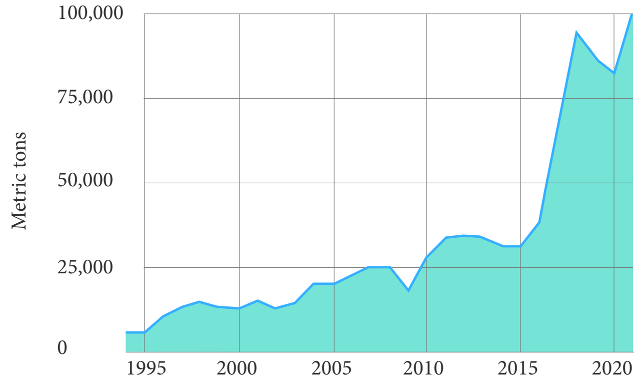

Figure 3. Lithium production from 1995-2022. This figure does not include US production (currently around 1,000). Source: USGS summaries 1994-2022.

800 percent higher for lithium carbonate and nearly 1,000 percent higher for lithium hydroxide than at the start of 2021.[39] Over time, high prices are expected to drive enough investment to meet demand. However, lithium mines take an average of 16.5 years to develop, which may create supply bottlenecks even with increasing investment.[40]

Before delving into existing forecasts of lithium demand and availability, it is worth underscoring the wide range in predictions, from large shortages to large surpluses.[41] This wide range suggests that there is currently no consensus or certainty about future market dynamics. It also reflects divergent modeling assumptions about the pace of EV adoption and the availability of alternative supplies from recycling feedstock, as well as expectations regarding the timeline to bring mines into production, with more sanguine predictions taking mining corporations at their word about how quickly their projects will develop. As discussed earlier, forecasts are not just about the future; they shape behavior in the present. Predictions of a supply gap incentivize a concerning race for extraction and buoy lithium prices, company profits, and stock values—while predictions of supply/demand equilibrium or even oversupply[42] tend to rely on corporate statements regarding production schedules, which are intended to attract investment and can be overly optimistic. Meanwhile, none of these models compares multiple pathways to zero-emissions transportation, as our material flow analysis does. For these reasons, a critical eye is always warranted when interpreting lithium forecasts.

Despite this diversity, all forecasts converge on one key point: the primary driver of lithium demand—and new lithium mines—is EVs. Global EV sales for 2022 are estimated to reach 10.6 million, a 60 percent increase from 2021 (and a 333 percent increase from 2020) that has been driven largely by China and Europe.[43]

The remainder of this section will highlight some existing modeling of lithium demand from the transportation and/or personal mobility sectors. These existing reports use some similar approaches to those used in this report, including defining scenarios for transportation and personal mobility decarbonization and estimating the lithium requirements of each scenario. As we will note, this report builds off these existing models by providing more detailed decarbonization scenarios that maintain existing or higher levels of personal mobility and can more drastically curtail lithium requirements.

BloombergNEF (BNEF)'s 2022 Electric Vehicle Outlook examines EV adoption and forecasts lithium demand into the future under two EV adoption scenarios: economic transition (an extrapolation of existing policies and market trends) and net zero (a decarbonized transportation system). In the net zero scenario, cumulative global lithium demand would reach 30.3 million metric tons in 2050, exhausting currently existing reserves by 2045, but could be cut in half with next-generation battery chemistries, which could lead to batteries that are more durable, charge faster, and store more energy per mass of lithium.[44] The report has a reduced demand scenario characterized by reduced car dependency with travel mode shifts to walking, cycling, and public transit; this leads to an approximately 15 percent reduction in the global car fleet in the report's forecast. When compared to BNEF's more moderate

39 Battery Materials," Fastmarkets, accessed October 28, 2022, https://www.fastmarkets.com/newgen/battery-materials.

40 International Energy Agency, "The Role of Critical Minerals in Clean Energy Transitions," IEA, Paris, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions, License: CC BY 4.0.

41 Mark Burton, "How Much Lithium Will the World Need? It Depends Who You Ask," Bloomberg.com, February 9, 2022, https://www.bloomberg.com/news/articles/2022-02-09/lithium-s-feast-or-famine-future-keeps-ev-makers-guessing.

42 For Goldman Sachs' recent oversupply predictions, see Sun, "Lithium Stocks Smashed after Bearish Notes from Goldman Sachs and Credit Suisse."

43 "The Road to Electric Car Supremacy in Five Charts," BloombergNEF, August 30, 2022, https://about.bnef.com/blog/the-road-to-electric-car-supremacy-in-five-charts/. It is worth noting that some lower- and middle-income countries are rapidly expanding e-mobility, in India's case with a focus on mopeds and rickshaws. See Emily Schmall, Jack Ewing, and Atul Loke, "India's Electric Vehicle Push Is Riding on Mopeds and Rickshaws," New York Times, September 4, 2022, https://www.nytimes.com/2022/09/04/business/energy-environment/india-electric-vehicles-moped-rickshaw.html.

44 McKerracher, "EV Outlook 2022."

economic transition scenario (which has EVs at 69 percent of the global passenger fleet in 2050), the reduced demand scenario produces a 433 GWh reduction in EV battery demand in 2050, which is more than all EV batteries sold in 2021 combined.[45] BNEF does not explicitly model the reduced demand for lithium that would likely accompany its reduced demand scenario.

The report of de Blas et al. (2020) takes a similar approach, with more significant variation across its adoption scenarios: expected EV trends, high EV, high e-bike, and degrowth.[46] For each scenario, the authors model cumulative lithium demand by 2050. The expected trends scenario projects current levels of car ownership with significant but incomplete EV adoption, resulting in 9.2 million metric tons of cumulative lithium demand. The high EV scenario also maintains existing levels of car ownership and requires 19.5 million metric tons of lithium—an amount nearly equal to the current global supply of lithium reserves. The high e-bike scenario would entail a large-scale shift from cars to micromobility modes and require 6.3 million metric tons of lithium, only a fraction of the high EV scenario requirements. The degrowth scenario pairs mass micromobility adoption with reduced overall transportation demand and would require 3.7 million metric tons.

While de Blas et al. make a valuable contribution, their report models the global transportation sector as a whole, with a tradeoff in terms of the specificity and number of scenarios. Blas et al. simplify the possible range of mode shares, and do not directly address vehicle ownership rates, EV battery sizes, or densification patterns. In contrast, our model focuses only on the US transportation sector and its potential decarbonization pathways.

Another model of global EV adoption and associated mineral demand from Benchmark Mineral Intelligence estimates that 59 to 74 new lithium mines would be needed by 2035 to meet its projected demand of 4 million metric tons per year, around 18 percent of existing reserves and an increase of 4,200 percent compared to current production.[47] The range (59–74) reflects uncertainty about recycling capacity and the role that recycled feedstock will play in satisfying lithium demand.

45 McKerracher, "EV Outlook 2022."

46 Ignacio de Blas, Margarita Mediavilla, Iñigo Capellán-Pérez, and Carmen Duce, "The Limits of Transport Decarbonization under the Current Growth Paradigm," Energy Strategy Reviews 32 (2020): 100543, https://doi.org/10.1016/j.esr.2020.100543.

47 Benchmark Mineral Intelligence, "More than 300 New Mines Required to Meet Battery Demand by 2035."

Finally, the International Energy Agency projects over 1.1 million metric tons of annual lithium demand by 2040 under their sustainable development scenario and estimates that the world will need around 2 billion EVs on the road by 2050 to reach net zero greenhouse gas emissions.[48] As of 2020, there were approximately 1.3 billion light-duty vehicles on the road, so this would represent a massive increase in the global passenger vehicle fleet and therefore reflects an assumption that car-centric transportation systems will be expanded around the globe.[49]

Replacing all of the ICE vehicles on the road with EVs on a 1:1 basis is infeasible, particularly on the urgent timeline needed for climate mitigation.[50] This would require significant increases in extraction of minerals like lithium and cobalt for EV battery packs and would also require an enormous amount of electricity. For the United States, researchers estimate that the 350 million EVs required to decarbonize the fleet in 2050 could use as much as half of US national electricity demand.[51] The issue of battery mineral demand is especially exacerbated in the United States given the current trend of large private vehicles like SUVs and trucks with long ranges. If this consumer behavior continues, along with US policy that is largely agnostic to the inefficiency and material intensity of EVs, the United States will require significantly more materials to manufacture its EV fleet and more electricity to power it. For example, the 2022 GMC Hummer EV pickup weighs over 9,000 pounds with a massive battery pack weighing almost 3,000 pounds, which is around three times the size of an average EV battery pack and hundreds of times the size of an electric bike battery pack.[52] The e-Hummer represents a more general, and concerning, trajectory: the sales-weighted average battery pack in the

48 International Energy Agency, "The Role of Critical Minerals in Clean Energy Transitions."

49 U.S. Energy Information Administration, "International Energy Outlook 2021," October 6, 2021, https://www.eia.gov/outlooks/ieo/.

50 Abdullah F. Alarfaj, W. Michael Griffin, and Constantine Samaras, "Decarbonizing US Passenger Vehicle Transport under Electrification and Automation Uncertainty Has a Travel Budget," Environmental Research Letters 15, no. 9 (2020): 0940c2, https://doi.org/10.1088/1748-9326/ab7c89.

51 Milovanoff et al., "Electrification of Light-Duty Vehicle Fleet Alone Will Not Meet Mitigation Targets."

52 Connor Hoffman and Dave VanderWerp, "EPA Documents Reveal More Specs on the 2022 GMC Hummer EV Pickup," Car and Driver, February 15, 2022, https://www.caranddriver.com/news/a39049358/2022-gmc-hummer-ev-pickup-epa-specs/.

Mode	Li/Rider Capacity	Li/ Battery
Hummer	4.8 kg	24 kg
EV	1.6 kg	8 kg
Bus	.52 kg	44 kg
eBike	.02 kg	.02 kg

Figure 4. Comparative chart of e-Hummer, EV, e-bus, and e-bike lithium intensities.

United States has increased in capacity by nearly threefold since the first commercial EV, the Nissan Leaf, hit the market about a decade ago. This increase is driven largely by Tesla EVs, which have typically had larger battery packs than other EVs and which currently comprise the largest volume of EVs on US roads.[53]

The question remains: would reducing the car dependency of the US transportation system translate to reduced demand for new lithium and new lithium mines? Aside from de Blas et al. (2020), no study has systematically compared the lithium intensity of distinct pathways to transportation decarbonization. Existing studies, except for de Blas et al. and BloombergNEF's reduced demand scenario, assume a trajectory of increasing car ownership over time, with the primary decarbonization strategy being the electrification of that growing global fleet while simultaneously decarbonizing the energy grid. But BloombergNEF does not test for lithium demand, and de Blas et al.'s global reach comes at the expense of specificity, or applicability to the unusually car-dependent United States.

This report thus makes multiple novel contributions. Identifying the range of decarbonization strategies, and their associated lithium volumes, is vital for many reasons. This report focuses on two sets of motivations for reducing the lithium intensity of the transition to zero-emissions transportation: first, the harmful impacts of lithium extraction (both ongoing, and planned), and second, the climate, environmental, and social benefits of shifting people in the United States out of their automobiles and into buses, bikes, and walkable streetscapes. We address each of these topics in the two sections that follow.

53 Hanjiro Ambrose, Alissa Kendall, Mark Lozano, Sadanand Wachche, and Lew Fulton, "Trends in Life Cycle Greenhouse Gas Emissions of Future Light Duty Electric Vehicles," Transportation Research Part D: Transport and Environment 81 (April 2020), https://doi.org/10.1016/j.trd.2020.102287.

EFFECTS OF LITHIUM EXTRACTION

Although lithium is geologically abundant, the vast majority of lithium extraction is concentrated in Australia, Chile, Argentina, and China. At the same time, the lithium extraction frontier is shifting to new regions as downstream battery and EV producers scramble to meet increasing demand, and governments, especially in China, the United States, Europe, and Canada, incentivize domestic extraction, expand domestic supply chains, and promote geopolitical alliances that facilitate trade in lithium and other "critical minerals." The result is intensified extraction within the countries that currently lead production, alongside prospecting and exploration in locales with previously small or non-existent lithium sectors.

Lithium can be found in a wide range of deposit types: rock, including both hard (pegmatite, most commonly spodumene) and soft (clay), and brine (including both continental salt flats and geothermal). In addition, lithium can be recovered from the "produced water" that is a byproduct of oil and gas production. All current operational lithium mines are either brine or hard rock; the rest of these deposit types (clay, geothermal, and oilfield) involve extraction techniques that have only been tested at the pilot scale. Thus, lithium extraction and processing projects can vary a great deal, and, with new extraction techniques, there remains considerable scientific uncertainty regarding the environmental consequences of commercial-scale production, including over water use and waste streams.[54]

Additionally, the type of lithium deposit is intertwined with needs for battery chemistry. Extraction from rock deposits produces lithium hydroxide, and extraction and evaporation from brine deposits produces lithium carbonate (although this can be converted into lithium hydroxide with further processing).[55] Lithium hydroxide is usable in high-nickel chemistries that enable longer driving ranges and do not require cobalt, which may make it more desirable for battery manufacturers and therefore incentivize extraction from rock deposits.[56][57]

54 Victoria Flexer, Celso Fernando Baspineiro, and Claudia Inés Galli, "Lithium Recovery from Brines: A Vital Raw Material for Green Energies with a Potential Environmental Impact in Its Mining and Processing," Science of the Total Environment 639 (October 2018): 1188–1204, https://doi.org/10.1016/j.scitotenv.2018.05.223.

55 Graham et al., "Lithium in the Green Energy Transition."

56 International Energy Agency, Global EV Outlook 2022: Securing Supplies for an Electric Future, OECD, 2022

57 "Mineral Commodity Summaries 2022"; "Albemarle to Double Silver Peak Lithium Production," 2021, Miningmagazine.com, January 8, 2021, https://www.miningmagazine.com/supply-chain-management/news/1402188/ablemarle-to-double-silver-peak-lithium-production.

Table 2: Global Lithium Mine Production (metric tons)

Country	2021 Production	Resource Type
Australia	55,000	Hard rock
Chile	26,000	Brine
China	14,000	Hard rock and brine
Argentina	6,200	Brine
Brazil	1,500	Hard rock
Zimbabwe	1,200	Hard rock
US	1,000	Brine
Portugal	900	Hard rock

Table 2: US lithium production is withheld from public access to avoid disclosing company proprietary data, as all production is currently from one mine, owned by Albemarle.[57]

Like all forms of mining, lithium extraction and processing comes with a number of concerning social and ecological impacts. These include pollution, water depletion, loss of biodiversity, threats to human rights, nonmining livelihoods, and Indigenous sovereignty and cultural integrity.

The threats to human rights and Indigenous sovereignty are especially pertinent given that much existing and proposed lithium mining is on or near Indigenous lands. **In the United States specifically, 79 percent of known lithium deposits sit within 35 miles of Native American reservations.**[58] Lithium mines on Indigenous lands have often been developed without substantive enforcement of Free, Prior and Informed Consent (FPIC), which is based on an international human right standard, the United Nations Declaration on the Rights of Indigenous Peoples, that allows Indigenous people the right to give or withhold permission for the advancement of projects that would affect them or their land, or substantive community participation. While many harms of mining may be mitigated, the destruction of sacred or tribal lands transforms landscapes permanently. The lack of substantive enforcement of FPIC and respect for Indigenous sovereignty is further discussed in the global case studies of mining sites below.

In this report, to illustrate the oftentimes devastating consequences of lithium mining, we focus on a subset of deposit types and geographies encompassing both ongoing and proposed lithium extraction. While not an exhaustive analysis of all projects and their impacts, our selection captures the range of current and potential harm. In addition, our selection was shaped by our organizational relationships with the five community reviewers that evaluated this report: Observatorio Plurinacional de Salares Andinos (encompassing directly affected communities and allies based in Chile, Argentina, and Bolivia); Fundación Ambiente y Recursos Naturales (based in Argentina); Great Basin Resource Watch (based in Nevada); the People of Red Mountain (based in Nevada); and representatives from Associação Unidos em Defesa de Covas do Barroso (based in Portugal). We thus focus on Chile, Argentina, and Nevada, plus Portugal, to capture the EU's plans for a massive increase in regional lithium mining. This selection excludes two critical sites of current global lithium production: Australia and China. There is limited independent research on both cases, but for an assessment of the sector's impacts in China see Gu and Gao (2021), and for a discussion of lithium mining's consequences in Australia, see Burgess et al. (2021).[59]

Despite the specificity of deposit types, extraction methods, and socio-natural landscapes, the selected cases illustrate a shared pattern of harm and risk. One persistent concern across sites is water. Depending on the method of extraction, water is used as an input in mining and/or processing, and/or a sink for waste and contamination, and/or is part and parcel of the deposit itself (in the case of brine[60]). Currently, the consumption and/or contamination of water is particularly high stakes as a result of climate change–induced drought. Indeed, every single one of the cases discussed below is situated in a drought-affected region.[61] More than half of global lithium production currently occurs in areas characterized by high water stress—an issue that will only get more salient as the climate crisis intensifies.[62] Information about these mining projects and their potential impacts is often not disseminated

58 Samuel Block, n.d., "Mining Energy-Transition Metals: National Aims, Local Conflicts," Msci.com, accessed November 23, 2022, https://www.msci.com/www/blog-posts/mining-energy-transition-metals/02531033947.

59 Guozeng Gu and Tianming Gao, "Sustainable Production of Lithium Salts Extraction from Ores in China: Cleaner Production Assessment," Resources Policy 74 (2021): 102261, https://doi.org/10.1016/j.resourpol.2021.102261; Claire Burgess, Liz Downes, and Nat Lowrye, "Is Australian Lithium the Answer to Zero Emissions?" Aid/Watch, September 23, 2021, https://aidwatch.org.au/wp-content/uploads/2021/09/Will-Australian-Lithium-Bring-Us-Zero-Emissions.pdf.

60 For discussion of brine as water, see James Blair, Ramón Balcázar, Javiera Barandirián, and Amanda Maxwell, "Exhausted: How We Can Stop Lithium Mining from Depleting Water Resources, Draining Wetlands, and Harming Communities in South America," April 26, 2022, Natural Resources Defense Council, accessed November 23, 2022, https://www.nrdc.org/resources/exhausted-how-we-can-stop-lithium-mining-depleting-water-resources-draining-wetlands-and; Mojtaba Ejeian, Alexander Grant, Ho Kyong Shon, and Amir Razmjou, 2021, "Is Lithium Brine Water?" Desalination 518 (2021): 115169, https://doi.org/10.1016/j.desal.2021.115169; Ingrid Garcés and Gabriel Álvarez, 2020, "Water Mining and Extractivism of the Salar DE Atacama, Chile," in Environmental Impact V (Southampton, UK: WIT Press), 189–199.

61 Jonathan Gilbert, "Drought, High Costs Push Argentine Farmers to Grow More Soy," Bloomberg.com, September 21, 2022, https://www.bloomberg.com/news/articles/2022-09-21/drought-soaring-costs-push-argentine-farmers-to-grow-more-soy; John Bartlett, "'Consequences Will Be Dire': Chile's Water Crisis Is Reaching Breaking Point," The Guardian, June 1, 2022, https://www.theguardian.com/world/2022/jun/01/chiles-water-crisis-megadrought-reaching-breaking-point; Colton Poore, "Nevada's Long-Term Dry Spell: Megadrought or New Normal?," Reviewjournal.com, Las Vegas Review-Journal, July 20, 2022, https://www.reviewjournal.com/local/local-nevada/nevadas-long-term-dry-spell-megadrought-or-new-normal-2608291; "Drought Prompts Portugal to Restrict Water Use at More Hydropower Dams," Reuters.com, September 22, 2022, https://www.reuters.com/business/environment/drought-prompts-portugal-restrict-water-use-more-hydropower-dams-2022-09-27/.

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transparently or equitably to impacted communities that are under-resourced when compared to corporations and governments.[63] Consequently, many existing and proposed projects have generated significant community resistance, which itself reflects a more general pattern of increasingly local skepticism toward large-scale mining projects, as well as communities' embrace of more militant, oppositional tactics to make their voices heard.[64]

Lastly, at the same time that global warming exacerbates the environmental harms of mining, mining directly contributes to the climate crisis, in two key ways. First, the mining sector accounts for 4–7 percent of global emissions (including emissions from both operations and power generation).[65] Second, large-scale mining and associated infrastructure can destroy the landscapes that function as vital carbon sinks. Tropical forests play a particularly pivotal role in this respect (hence condemnation of mining and other extractive industries in the Amazon); however, deserts—a label that applies to several sites discussed below—are also carbon sinks.[66]

63 Araceli Clavijo, Walter F. Díaz Paz, Mauricio Lorca, Manuel Olivera Andrade, Martín A. Iribarnegaray, and Ingrid Garcés, "Environmental Information Access and Management in the Lithium Triangle: Is It Transparent Information?" Journal of Energy & Natural Resources Law (2022): 1–22, https://doi.org/10.1080/02646811.2022.2058770.

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65 Taylor Kuykendall, Katya Bouckley, Filip Warwick, Stephanie Tsao, and Guarang Dholakia, "Mining Faces Pressure for Net-Zero Targets as Demand Rises for Clean Energy Raw Materials," S&P Global Commodity Insights, July 27, 2020, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/coal/072720-mining-faces-pressure-for-net-zero-targets-as-demand-rises-for-clean-energy-raw-materials.

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Hard Rock and Clay

Rock extraction is done by digging out ores, primarily spodumene, from huge open pit mines and using sulfuric acid to dissolve excess minerals, leaving lithium and other valuable metals behind. Australia, currently the world's top producer, gets its lithium from hard rock extraction. Rock deposits yield higher concentrations of lithium than brine, but the extractive process is more complex and expensive, has higher greenhouse gas emissions, and uses more freshwater.[67] It produces significant pollution from the waste tailings left behind after the acid processing. Adding to the emissions intensity, more than 90 percent of Australia's lithium concentrate is shipped to China for further processing.[68]

United States

Mining regulation in the United States is overall deficient and seriously outdated. On federal public lands, mining is still primarily governed by the General Mining Act of 1872, which contains no water or environmental safeguards nor provisions for Indigenous consultation, let

67 Cristina Chaves, Elma Pereira, Paula Ferreira, and António Guerner Dias, "Concerns about Lithium Extraction: A Review and Application for Portugal," Extractive Industries and Society 8, no. 3 (2021): 100928, https://doi.org/10.1016/j.exis.2021.100928; Jarod C. Kelly, Michael Wang, Qiang Dai, and Olumide Winjobi, "Energy, Greenhouse Gas, and Water Life Cycle Analysis of Lithium Carbonate and Lithium Hydroxide Monohydrate from Brine and Ore Resources and Their Use in Lithium Ion Battery Cathodes and Lithium Ion Batteries," Resources, Conservation and Recycling 174 (2021): 105762.

68 "Insights into Australian Exports of Lithium," Australian Bureau of Statistics, April 8, 2022, https://www.abs.gov.au/articles/insights-australian-exports-lithium.

alone consent. At present, only one small lithium mine operates in the US: Silver Peak, a brine deposit located in southwest Nevada and run by the Albemarle Corporation that currently produces just under 1,000 metric tons of lithium per year.[69] However, the drive to onshore US lithium mining points to a significant increase in rock extraction. Near the end of the Trump administration in early 2021, the US Department of the Interior's Bureau of Land Management approved a massive new lithium project on leased federal lands a few hundred miles away in northwestern Nevada's Humboldt County called Thacker Pass. Thacker Pass is the site of a large soft clay lithium deposit. Lithium Nevada, the corporation developing the project and a subsidiary of Lithium Americas, claims that it can produce 30,000 metric tons of lithium per year, which if it were a country would make the Thacker Pass project the second largest producer of lithium in the world.[70]

The proposed mining at Thacker Pass would disturb approximately 5,695 acres and last for 41 years, and at the end of its operating span the open pit mine would be entirely filled in.[71] Once up and running, the mining operation would use approximately 5,200 acre-feet of water per year (equivalent to the water usage of around 15,000 US households) from a nearby groundwater well.[72] It would also produce 354 million cubic yards of clay tailings waste over its lifespan using novel technology, which has the potential to leak and contaminate area soil and water.[73]

This project has faced significant local resistance from various groups, including environmentalists, ranchers, and Indigenous tribes, because of a lack of consultation with local tribes and an inadequate environmental review. The definite or potential ecological impacts of Thacker Pass include groundwater depletion, pollution, and habitat destruction for species like sage grouse, golden eagles, Lahontan cutthroat trout, and pronghorn antelopes.[74] Ranchers in particular are concerned that the mine's water usage will negatively impact their cattle grazing operations. Additionally, Atsa Koodakuh wyh Nuwu (People of Red Mountain) is a group of Fort McDermitt Paiute and Shoshone Tribe members organizing against this project proposed for the land they call Peehee Mu'huh (rotten moon). This area has cultural and spiritual significance to tribal members because they harvest traditional foods and medicinal plants in the area. Peehee Mu'huh is also the site of multiple massacres of Indigenous people by US soldiers, including the killing of dozens of Paiute people in 1865.[75] The exact locations of victims' graves remain unknown; documents that are available do not specify them. The last Indian massacre recorded in the area occurred in February 1911, near the Santa Rosa mountains. Unlike some other forms of harm, cultural harms like desecrating sacred land have no possibility for mitigation.

A coalition of ranchers (Edward Bartell), Indigenous groups (the People of Red Mountain, the Burns Paiute Tribe, and the Reno-Sparks Indian Colony), and environmental justice organizations (Great Basin Resource Watch, Basin and Range Watch, and Wildlands Defense) have sued the Bureau of Land Management seeking to stop the Thacker Pass mine.[76] This lawsuit has a hearing set for January 5, 2023, and may be the last remaining legal hurdle for the project to proceed.[77]

69 "Albemarle to Double Silver Peak Lithium Production."

70 Graham et al., "Lithium in the Green Energy Transition."

71 US Bureau of Land Management, "Thacker Pass Lithium Mine Project Final Environmental Impact Statement," December 4, 2020, https://eplanning.blm.gov/public_projects/1503166/200352542/20030633/250036832/Thacker%20Pass_FEIS_Chapters1-6_508.pdf.

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73 Steven H. Emerman, n.d., "Prediction of Seepage from the Clay Tailings Filter Stack (CTFS) at the Lithium Nevada Thacker Pass Mine, Northern Nevada," Great Basin Resource Watch, https://www.gbrw.org/wp-content/uploads/2022/06/Exhibit-4-Thacker_Pass_Report_Emerman_Revised2.pdf; Ivan Penn, Eric Lipton, and Gabriella Angotti-Jones, "The Lithium Gold Rush: Inside the Race to Power Electric Vehicles," New York Times, May 6, 2021, https://www.nytimes.com/2021/05/06/business/lithium-mining-race.html.

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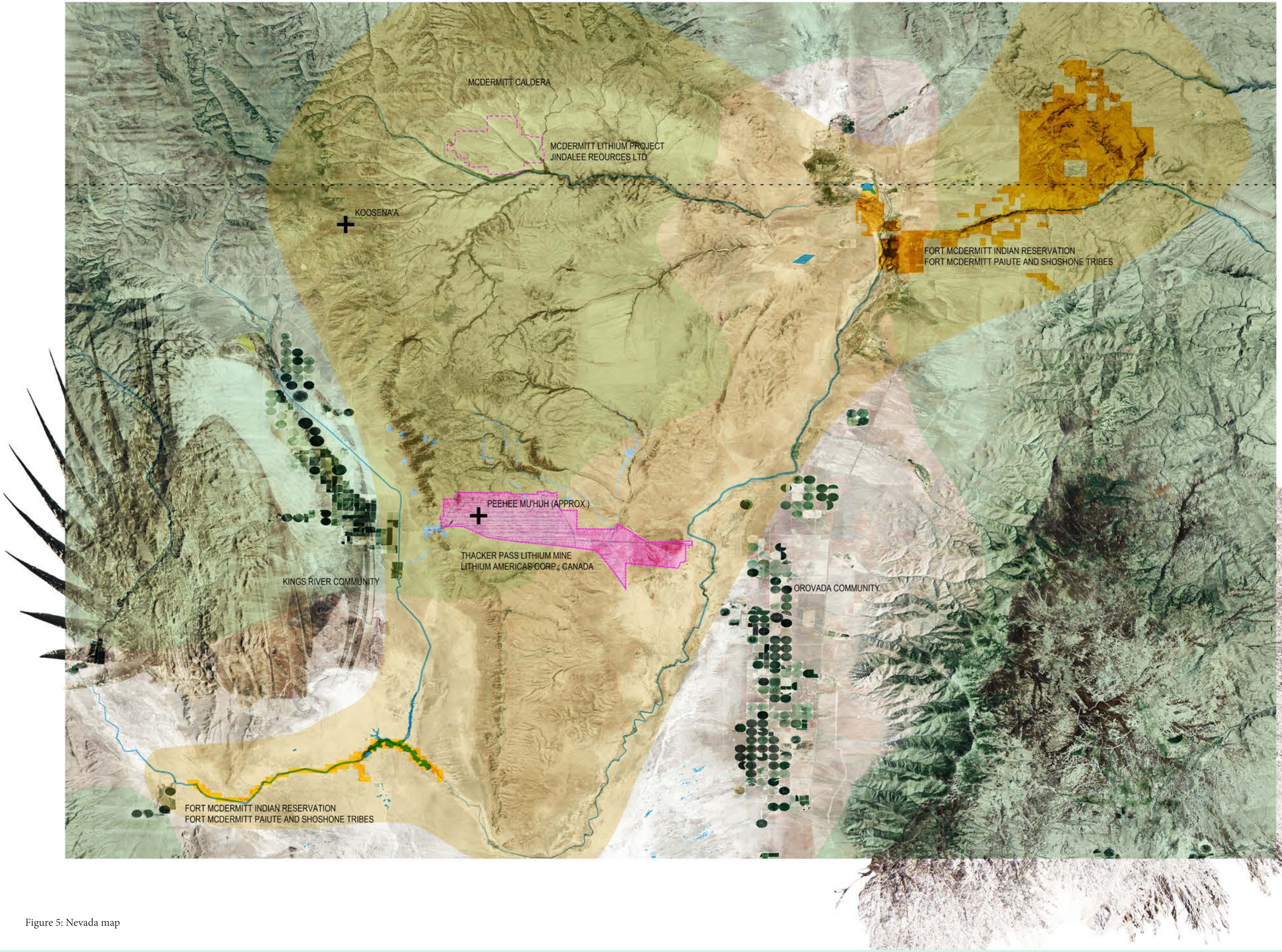
77 "U.S. Court Sets January 2023 Hearing for Lithium Americas Mine Suit," Reuters, October 6, 2022, https://www.reuters.com/legal/us-court-sets-january-2023-hearing-lithium-americas-mine-suit-2022-10-06/.



Thacker Pass, Nevada, USA

Reservation
Sacred Land
+ Significant Indigenous Place
Mining Concession
Disturbance Area
Water
Perennial Streams and Springs
Extreme Drought (2022)
Sagebrush

0 17000'

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Figure 5: Nevada map

Portugal

Portugal has the largest lithium reserves in Europe.[78] However, at 60,000 metric tons, it is still relatively small when compared to the reserves of major producers like Australia and Chile. In 2021, Portugal was producing low-grade lithium for glass and ceramics usage, which accounted for just under 1 percent of global lithium production.[79]

In the wake of the 2008 financial crisis, Portugal took on loans from the EU and the International Monetary Fund that came with structural adjustment policies to incentivize exploration for potential new lithium mining and processing; similarly, the European Battery Alliance and Raw Material Alliance has promoted extraction among EU member states, helping to coordinate supply chains and secure project funding.[80] The EU wants to have a more self-reliant supply chain for the energy transition, and the Portuguese government has been approving new exploration for lithium. [81]

British mining company Savannah Resources has proposed the Barroso lithium mine in northeastern Portugal, which would be the largest lithium mine in Europe. But this project has been delayed for years because of ongoing environmental reviews and community resistance.[82] The Barroso mine would produce around 14 million metric tons of tailings over 12 years, which would be enclosed by waste rock. If the waste mound fails, the potentially toxic tailings waste could flow into nearby rivers.[83] Many residents of Barroso live off the land, particularly through "agro-sylvo-pastoral"–smallholder agriculture; this project presents a direct threat to their environment and their livelihoods.[84] Indeed, the Barroso region is designated a Globally Important Agricultural Heritage System by the Food and Agriculture Organization of the United Nations.[85] The Local Community of Common Land of Covas do Barroso has filed a lawsuit against Savannah Resources claiming that the parcel they purchased for the mine is on land that has long been held in common—land that cannot be sold and is managed jointly by community members.[86]

78 Chaves et al., "Concerns about Lithium Extraction: A Review and Application for Portugal."

79 Felix Malte Dorn, "Inequalities in Resource-Based Global Production Networks: Resistance to Lithium Mining in Argentina (Jujuy) and Portugal (Região Norte)," Journal für Entwicklungspolitik 37, no. 4 (2021): 70–91; "Mineral Commodity Summaries 2022."

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81 Leonie Kijewski, "Portuguese Villagers Fear Hunt for Lithium Will Destroy Their Livelihoods," Politico, April 27, 2022, https://www.politico.eu/article/portugal-village-fear-hunt-lithium-destroy-livelihood/.

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83 Steven H. Emerman, n.d., "Evaluation of the Tailings Storage Facility for the Proposed Savannah Lithium Barroso Mine, Northern Portugal," Unece.org, accessed November 23, 2022, https://unece.org/sites/default/files/2021-10/frCommC186_13.10.2021_annex3_eng.pdf.

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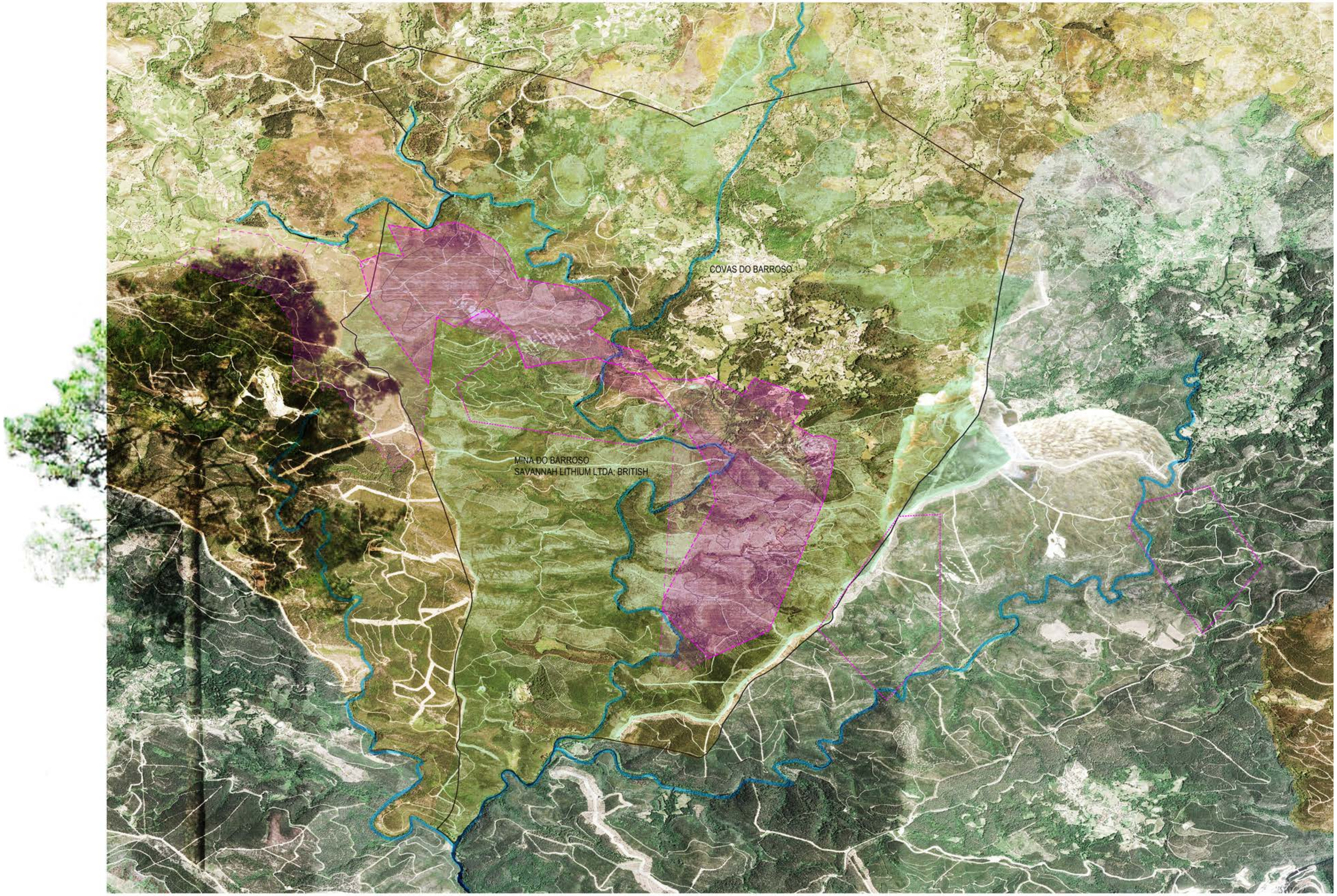

Portugal

- Barroso (GIAHS)
- Baldios
- Mine Limit
- Mining Concession
- Mining Concession Blocks
- Debris piles
- Water
- Drought (2022)

0 — 2000'

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Figure 6: Portugal map

Brine

Lithium found in brine deposits is extracted by pumping the brine out of underground aquifers, then concentrating the brine to increase the percentage of lithium salts. Typically, this concentration is achieved via evaporation from large pools under the sun until the lithium levels reach approximately 6 percent of the solution,[87] a process that takes around a year to complete. Producing 1 metric ton of lithium in this manner requires evaporating approximately 2 million liters of water from brine.[88]

This extraction process leaves behind piles of waste salts and toxic chemicals and appears to have significant deleterious impacts on local freshwater stores and ecosystems, including iconic flora and fauna such as the two of the three flamingo species endemic to the area[89] and microbial life for which the brine is a habitat.[90] The environmental consequences of brine extraction are a form of "slow violence": less immediately visible because they are generally less direct and more gradual, but cumulatively harmful, particularly given the proximity of other large-scale extractive sectors (especially copper) resulting in compounding impacts.[91] Unfortunately, there is a dearth of independent scientific studies regarding specifically how brine extraction interacts with freshwater aquifers and some debate among scientists on the subject; a great deal of corporate self-monitoring and research funding further muddies the waters.[92]

Direct lithium extraction (DLE) is an emerging technology that actively extracts lithium and other desired minerals from brines, allowing the rejected brine stream to be pumped back underground. This process could significantly reduce environmental impacts of brine extraction. Industrial-scale DLE methods have been proposed in Germany, Argentina, and California's Salton Sea region, where lithium-rich geothermal brines can provide geothermal energy and lithium, but this technology has yet to be proven at scale (US-based Livent does use DLE at its Fénix lithium project in the Salar de Hombre Muerto in Catamarca, Argentina, although the brine is first pre-concentrated using the traditional evaporation technique[93]).

Brine extraction is how lithium is mined in the so-called Lithium Triangle of Chile, Argentina, and Bolivia thousands of feet above sea level in the Andes Mountains. This area contains more than half of both global resources and reserves, and it is where nearly one-third of current global lithium production comes from.[94]

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93 Graham et al., "Lithium in the Green Energy Transition."

94 "Mineral Commodity Summaries 2022."

Chile

Chile is the second-largest producer of lithium in the world, trailing only Australia at 26,000 metric tons in 2021. In Chilean law, brine is treated as a mineral rather than water, and mining is regulated at the federal level. Lithium was declared a strategic resource and nonconcessionable in 1979, which has in effect limited the number of mining projects to those with concessions that predate this statutory change.[95] Currently, two large-scale lithium mines are in production on the Atacama Salt Flat, operated by SQM and Albemarle. However, the country's state-owned copper company, Codelco, plans to explore and exploit lithium in the Maricunga Salt Flat, as does Minera Salar Blanco, a joint Australian-Chilean-Canadian venture.[96] In January 2022, a tender for new lithium contracts was suspended by Chile's Supreme Court on the grounds that the auction did not specify specific territories and thus made prior consultation of Indigenous peoples impossible; however, the progressive Boric government has had plans to establish a state-owned company and enter into joint ventures with foreign lithium companies.[97]

The Atacama Salt Flat is surrounded by Andean mountains and is located in the Atacama Desert, the oldest and driest desert in the world.[98] Lithium extraction in Chile threatens the health and viability of Atacama ecosystems, which are important for local communities and humanity more broadly. Scientists recently identified plants in the Atacama that are adapted to the arid conditions and genetically similar to food crops, which means they may be highly useful for adapting agriculture to a warming planet.[99]

The ecological impacts of brine extraction in Chile, particularly its water usage, have come under increasing scrutiny. Earlier this year, the Chilean government sued lithium mining company Albemarle (along with Antofagasta and BHP for their copper mines) because of their exploitation of the Monturaqui-Negrillar-Tilopozo aquifer and impact on surrounding ecosystems.[100] The other major lithium mining company operating in Chile, Sociedad Química y Minera de Chile (SQM), has been subject to numerous investigations and lawsuits for labor, financial, and environmental violations.[101] For example, in 2016 Chilean regulators initiated sanctions against SQM for overconsuming freshwater and brine, and also for tampering with their own environmental monitoring systems.[102] In January 2019, regulators accepted a company plan to bring its operations into compliance with its contract and Chilean law.[103] But later that same year, the Council of Atacameño Peoples (Consejo de Pueblos Atacameños, or CPA)—which represents the 18 Indigenous Atacameño communities that live around the Atacama Salt Flat—successfully appealed the plan. Their appeal forced the company back to the drawing board, resulting in a new commitment to cut brine and water use in half—though it certainly remains to be seen whether the company will achieve these goals.[104]

95 Florencia Heredia, Agostina L. Martinez, and Valentina Surraco Urtubey, "The Importance of Lithium for Achieving a Low-Carbon Future: Overview of the Lithium Extraction in the 'Lithium Triangle,'" Journal of Energy & Natural Resources Law 38, no. 3 (2020): 213–36, https://doi.org/10.1080/02646811.2020.1784565.

96 "Chile Copper Giant Codelco to Start Lithium Exploration in March," Reuters, February 16, 2022, https://www.reuters.com/business/energy/chile-copper-giant-codelco-start-lithium-exploration-march-2022-02-16/; "Salar DE Maricunga, Atacama, Chile," AID/WATCH | Exposing Bad Aid for over 30 Years, September 23, 2021, https://aidwatch.org.au/case-studies/salar-de-maricunga-atacama-chile/.

97 Mining.com, accessed November 23, 2022, https://www.mining.com/web/chiles-mining-minister-says-country-open-to-new-lithium-tenders/.

98 Alan T. Bull, Juan A. Asenjo, Michael Goodfellow, and Benito Gómez-Silva, "The Atacama Desert: Technical Resources and the Growing Importance of Novel Microbial Diversity," Annual Review of Microbiology 70, no. 1 (2016): 215–34, https://doi.org/10.1146/annurev-micro-102215-095236.

99 Gil Eshel, Viviana Araus, Soledad Undurraga, Daniela C. Soto, Carol Moraga, Alejandro Montecinos, Tomás Moyano, et al., "Plant Ecological Genomics at the Limits of Life in the Atacama Desert," Proceedings of the National Academy of Sciences of the United States of America 118, no. 46 (2021): e2101177118, https://doi.org/10.1073/pnas.2101177118.

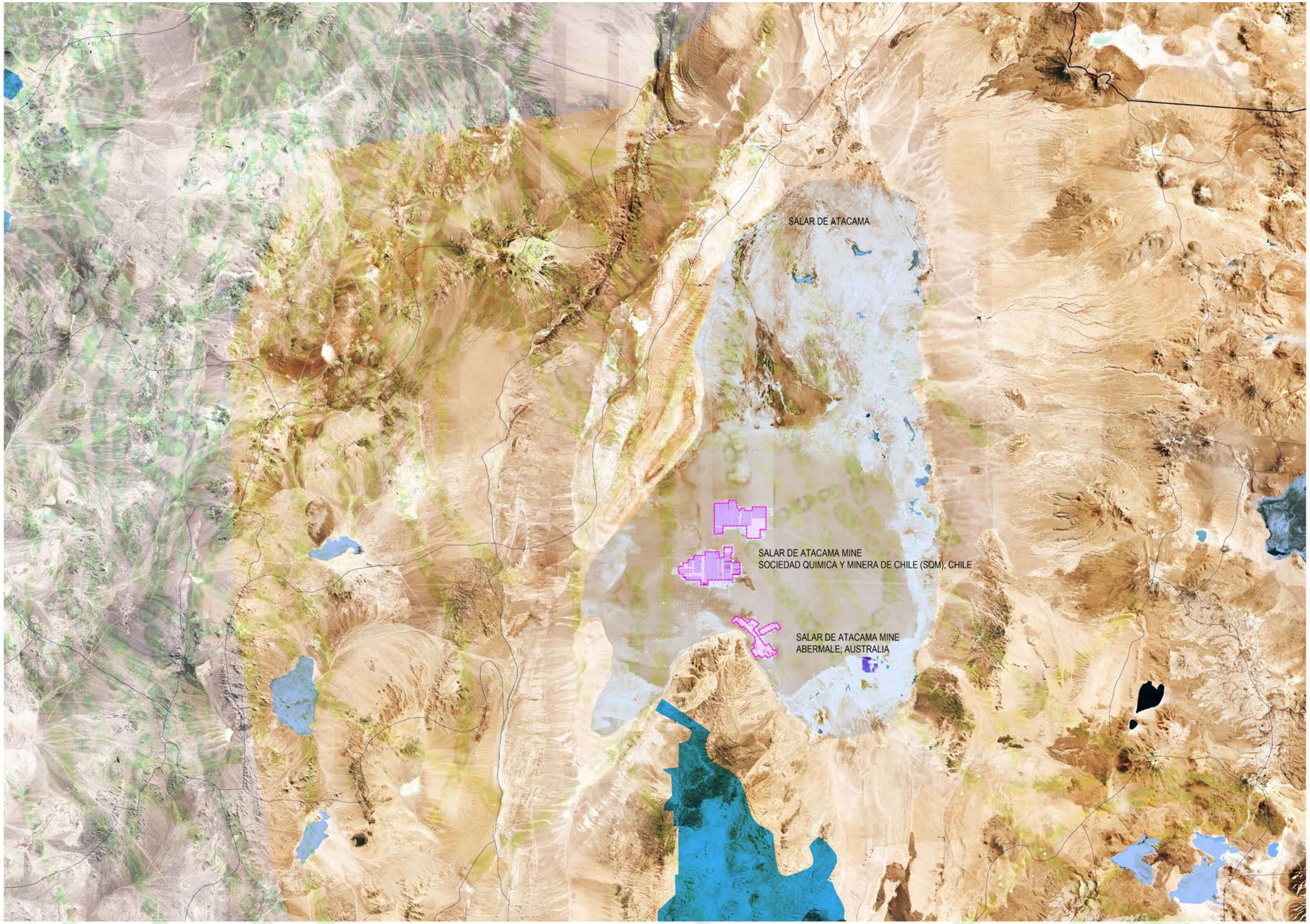
100 Cecelia Jamasmie, "Chile Sues BHP, Albemarle, Antofagasta over Water Use," Mining.com, April 8, 2022, https://www.mining.com/chile-sues-bhp-albemarle-antofagasta-over-water-use/.

101 Jerez et al., "Lithium Extractivism and Water Injustices in the Salar de Atacama, Chile."

102 Willie Shubert, "Chile Renews Contract with Lithium Company Criticized for Damaging Wetland," Mongabay Environmental News, December 26, 2018, https://news.mongabay.com/2018/12/chile-renews-contract-with-lithium-company-criticized-for-damaging-wetland/.

103 "Chile: Detienen Proceso Sancionatorio de SQM Acusada de Graves Infracciones Ambientales," Noticias Ambientales, January 22, 2019, https://es.mongabay.com/2019/01/chile-detienen-sanciones-por-danos-ambientales-en-salar-de-atacama/.

104 Aislinn Laing, "Chilean Lithium Miner SQM Dealt Blow by



Chile

- Atacamenos/Lickantay Lands
- Lithium Mines
- Water
- Monturaqui-Negrillar-Tilopozo Aquifer
- Watersheds
- Drought (2022)

0 19,000'

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Figure 7: Chile map

Given this long history of lithium companies violating regulations, lithium mining has faced opposition from a variety of groups in Chile. It has also generated serious tension and division within affected Indigenous communities in large part because of the economic resources the companies promise.[105]

Argentina

Argentina is the fourth-largest producer of lithium in the world—6,200 metric tons in 2021—but it has around 50 proposed projects, which could dramatically increase its production and push it above Chile and China.[106] As in Chile, lithium mining creates tensions within communities because of the trade-offs between economic and infrastructural benefits offered by corporations (that are lacking from the government) versus the social and ecological harms that mining causes, a contradiction that companies can exploit to their advantage.[107] Brine extraction threatens nearby Indigenous pastoralism and the unique wetlands full of important biodiversity, including species like flamingos, "pumas, Andean foxes, vicuna [sic], hairy armadillos, and endangered Andean mountain cats and short-tailed chinchillas."[108]

Mining regulation is mostly decentralized in Argentina and varies significantly at the provincial level.[109] This is the result of federal deregulation in response to structural adjustment in the early 1990s, which also provided corporations with incentives to mine; previously, natural resources were owned by the federal government.[110] This "localized governance" does not correlate to addressing community concerns around lithium mining projects; a multinational mining company and a provincial government or an Indigenous community are often on unequal footing in terms of negotiations.[111]

As a signatory of the UN Declaration on the Rights of Indigenous Peoples, the Argentinean government is ostensibly supposed to obtain Free, Prior and Informed Consent from Indigenous peoples for lithium extraction that affects their lands. However, as in other countries, community members near lithium mining in Argentina have noted a lack of information from both companies and governments on the potential risks and negative environmental impacts of these projects.[112] Resistance to lithium extraction projects varies significantly between and within provinces, as a result of factors like power and resources of local Indigenous movements, proximity to population centers, and provincial government policies for mining.[113][114]

Environmental Court Ruling," Reuters, December 27, 2019, https://www.reuters.com/article/us-chile-sqm-idUSKBN1YV05T; "Chile Lithium Producer SQM Gets Green Light on Environmental Plan," Reuters, August 30, 2022, https://www.reuters.com/business/sustainable-business/chile-lithium-producer-sqm-gets-green-light-environmental-plan-2022-08-30/.

105 Jerez et al., "Lithium Extractivism and Water Injustices in the Salar de Atacama, Chile"; Guillaume Peterson St-Laurent and Philippe Le Billon, "Staking Claims and Shaking Hands: Impact and Benefit Agreements as a Technology of Government in the Mining Sector," The Extractive Industries and Society 2, no. 3 (2015): 590–602, https://doi.org/10.1016/j.exis.2015.06.001.

106 Fred Pearce, "Why the Rush to Mine Lithium Could Dry Up the High Andes," Yale Environment 360, September 19, 2022, https://e360.yale.edu/features/lithium-mining-water-andes-argentina.

107 Lucas Isaac Gonzalez and Richard Snyder, "Modes of lithium extraction in Argentina: Mining politics in Catamarca, Jujuy, and Salta," 2020.

108 Pearce, "Why the Rush to Mine Lithium Could Dry Up the High Andes."

109 Heredia et al., "The Importance of Lithium for Achieving a Low-Carbon Future."

110 Dorn, "Inequalities in Resource-Based Global Production Networks: Resistance to Lithium Mining in Argentina (Jujuy) and Portugal (Região Norte)"; Gonzalez and Snyder, "Modes of lithium extraction in Argentina: Mining politics in Catamarca, Jujuy, and Salta." Natural resources and policy choices in Latin America.

111 Gonzalez and Snyder, "Modes of Extraction in Latin America's Lithium Triangle: Explaining Negotiated, Unnegotiated and Aborted Mining Projects," Latin American Politics and Society, forthcoming 2022.

112 Pía Marchegiani, Jasmin Höglund Hellgren, and Leandro Gómez, "Lithium Extraction in Argentina: A Case Study on the Social and Environmental Impacts," n.d., FARN, https://goodelectronics.org/wp-content/uploads/sites/3/2019/05/DOC_LITHIUM_ENGLISH.pdf.

113 Gonzalez and Snyder, "Modes of lithium extraction in Argentina"; Javiera Barandiarán, "Lithium and Development Imaginaries in Chile, Argentina and Bolivia," World Development 113 (2019): 381–91, https://doi.org/10.1016/j.worlddev.2018.09.019.

114 Marconi et al., "The Arid Andean Plateau Waterscapes."

Argentina

- Indigenous land
- Provincial Boundary
- Lithium Mines
- Mining Concession Blocks
- Debris piles
- Water
- Flamingo Frequency
- Drought (2022)

0 — 66,000'

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"OLAROZ LITHIUM FACILITY - Orocobre Limited." n.d. Accessed November 6, 2022. https://www.orocobre.com/operations/salar-de-olaroz/.

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Figure 8: Argentina map. Besides the projects depicted in this map, three more projects have been approved for the start of exploitation (Sal de Vida, Sal de Oro, and Tres Quebradas) in Catamarca, in addition to multiple other projects that are currently under exploration and prospecting.[114]

PATHWAYS TO DECARBONIZED TRANSPORTATION

There are multiple ways to decarbonize personal mobility in the United States and elsewhere. Different transportation systems—the mix of transportation modes that people use to get around, and the infrastructures and surrounding land uses that permit or foreclose them—will have different sets of features; they may increase or decrease people's mobility options and ease of movement. They will have different resource intensities, mandating more or less socially and ecologically destructive mining and leading to more or less vulnerability of global supply chains for "critical minerals." Different transportation futures also represent varying levels of death and serious injuries from crashes or accidents. They will entail more or fewer abbreviated years of healthy life from pollution, including from tire and brake dust.[115] Different transportation futures may demand more or less money from household and government budgets;[116] they may improve or subtract from quality of life and life expectancies and allow more or less plausible decarbonization pathways. Different transportation systems will be more or less supportive of economic prosperity; more or less destructive of global ecosystems, cultures, and communities; and more or less geopolitically destabilizing.

This report quantifies the lithium resource intensity of four possible zero-emissions transportation systems as they pertain to personal mobility in the United States, ranging from the continuation of the status quo, characterized by car dependency, to increasingly ambitious alternate scenarios with increased transit options and decreased private car ownership rates. Modeling these scenarios required definition of the specific, material differences between these possible decarbonized transportation futures, including the quantities, varieties, and sizes of EVs.

115 Because a large share of deadly air pollution from car traffic comes from particulate dust from road, tire, and brake wear, a shift to EVs will not reduce, and may even increase, major types of air pollution. See Ye Liu, Haibo Chen, Jianbing Gao, Ying Li, Kaushali Dave, Junyan Chen, Matteo Federici, and Guido Perricon, "Comparative Analysis of Non-Exhaust Airborne Particles from Electric and Internal Combustion Engine Vehicles," Journal of Hazardous Materials 420 (October 15, 2021), https://doi.org/10.1016/j.jhazmat.2021.126626.

116 Margy Waller, n.d., "High Cost or High Opportunity Cost? Transportation and Family Economic Success," Brookings, https://www.brookings.edu/research/high-cost-or-high-opportunity-cost-transportation-and-family-economic-success-2/; Todd Litman, "Automobile Dependency: An Unequal Burden," December 15, 2020, https://www.planetizen.com/blogs/111535-automobile-dependency-unequal-burden.

This report focuses on land-based personal mobility; we do not model freight transportation. Currently, transportation is the leading cause of greenhouse gas emissions in the United States, and the only sector in which emissions are still steadily rising. Within the surface transportation sector, 57 percent of emissions in the United States come from light-duty vehicles—cars, trucks, and SUVs—and 26 percent from on-road freight, and the remainder from nonroad modes including air, rail, and barge.[117] Our focus on land-based personal mobility therefore covers the majority, but not the entirety, of the transportation sector. However, many strategies that could reduce resource intensity of personal mobility may have analogs in the freight and shipping portions of the transportation sector (for example, moving goods by trains rather than trucks[118]). The co-benefits of eliminating air quality pollutants via electrification of the freight sector may be particularly important from an environmental justice perspective. A recent report from the American Lung Association estimates that electrifying heavy trucks could reduce premature death due to air pollution by 66,000, benefiting people in communities that already are disproportionately burdened by pollution.[119]

We found that scenarios with fewer vehicles and/or smaller ones required less lithium. Scenarios where the average US household has multiple, very large private EVs would require significantly more lithium, driving a surge in new mining and leading to the disruption or destruction of more ecosystems and human communities compared to a transportation future where electrified rail, active transit, and/or car-share systems predominate over mass private car ownership. The former scenario would also pose supply chain bottlenecks that would slow feasible EV adoption (and therefore decarbonization), and may come up against economic and technical constraints posed by the limited extractability of global lithium deposits.[120]

117 US EPA, Oar. 2015, "Fast Facts on Transportation Greenhouse Gas Emissions," https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions; Sindreu, "In the Green Transition, Transportation Is the next Big Baddie."

118 Alison Schafer and Martha Lawrence, "Decarbonizing Transport: Shifting People and Goods onto Railways," World Bank Blogs (blog), n.d., World Bank Group, https://blogs.worldbank.org/transport/decarbonizing-transport-shifting-people-and-goods-railways.

119 American Lung Association, "Delivering Clean Air: Health Benefits of Zero-Emission Trucks and Electricity," n.d., https://www.lung.org/getmedia/e1ff935b-a935-4f49-91e5-151f1e643124/zero-emission-truck-report.

120 Alexandra Pehlken, Sabine Albach, and Thomas Vogt, "Is There a Resource Constraint Related to Lithium Ion Batteries in Cars?" International Journal of Life Cycle Assessment 22, no. 1 (2015): 40–53,

Prior studies have shown that electrification of the current US personal transportation system is insufficient to keep global warming under a 2°C increase, and that "demand-side solutions" (i.e., reducing private car use) are also an urgent need.[121] By spotlighting the resource intensities—especially the lithium intensities—of different pathways to decarbonizing transportation, this report builds the argument for transportation horizons that consider the social and environmental implications of whole supply chains. As vast and horrifying as the effects of the climate crisis are and will be, especially as warming surpasses the 1.5°C mark, "critical mineral" mining entails its own starkly negative consequences that deserve their own discussion.[122]

Decarbonization modeling often relies on shared socioeconomic pathways (SSPs) to define how future scenarios may meet or fail to meet the carbon budgets for different levels of global warming. In order to model lithium intensities, we define SSPs for personal transportation decarbonization. This section defines these different SSPs, drawing international comparisons to determine achievable scenarios for different decarbonized transportation systems. First, we define the SSPs or decarbonized mobility scenarios in general terms. Then, we discuss in more detail how we arrived at these scenarios and used data on existing global transportation patterns to construct these scenarios and determine vehicle needs for each of them.

Overview of Decarbonized US Transportation Scenarios

We include four transportation scenarios, with different types and categories of vehicles in use. This section presents an overview, and more details on our methodology and the data that informed these scenarios can be found in the section in the appendix, "Building Decarbonization Pathways from Data on Global Transportation Systems." See Table 1 for the four decarbonized mobility scenarios

Each of these scenarios reflect ambitious changes from our current transportation system.

Scenario 1 may, on the surface, seem to require the least dramatic changes, but it is not at all obvious that this would be the case. First, based on prior research, this scenario is likely incompatible with the sectoral carbon budget to limit warming to 1.5°C or even 2°C of warming;[123] it would likely therefore be paired with the greatest damage, disruptions, and upheavals from the climate crisis of all the scenarios. Scenario 1 is also the most lithium-intensive scenario and likely the most resource-intensive scenario overall; it would require the most land dedicated to transportation, and likely the most materials and labor to realize. While the United States has an enormous amount of embedded car-oriented infrastructure, this infrastructure deteriorates: the interstate highways system was built to last 50 years; asphalt roads tend to last 18 years.[124] The United States has embedded institutional infrastructure that is accustomed to building car dependency, but it is not apparent that this scenario would be the most minor undertaking in terms of physical resources or organizational capacity required—even leaving aside the likelihood of catastrophically worse climate impacts in this scenario.

Faced with the abject urgency of decarbonization—but also the host of health, safety, quality of life, and other social and economic costs of car dependency—cities have already begun to realize dramatic mode shifts in line with our scenarios in matters of 10—20 years. In Paris, car use declined nearly 30 percent from 2001 to 2015, and has been continuing to fall since then; in Lyon, the number of cars entering the city declined 20 percent over 10 years; in London, car use fell by nearly 40 percent from 2000 to 2014.[125] In Amsterdam, the share of trips by bicycle, which had plummeted nearly 60 percentage points over two decades, began to rise dramatically again in the 1970s after the city began to implement policy and infrastructural shifts in response to activism from street safety and cycling advocates, which reversed the city's emergent car dependency.[126] While the mode shifts in our

https://doi.org/10.1007/s11367-015-0925-4.

121 Milovanoff et al., "Electrification of Light-Duty Vehicle Fleet Alone Will Not Meet Mitigation Targets."

122 Brad Plumer, Raymond Zhong, and Lisa Friedman, "Time Is Running Out to Avert a Harrowing Future, Climate Panel Warns," New York Times, February 28, 2022, https://www.nytimes.com/2022/02/28/climate/climate-change-ipcc-un-report.html?smid=url-share.

123 Milovanoff et al., "Electrification of Light-Duty Vehicle Fleet Alone Will Not Meet Mitigation Targets."

124 "America's Interstate Highway System at 65: Meeting America's Transportation Needs with a Reliable, Safe & Well-Maintained National Highway Network," TRIP National Transportation Research Nonprofit, June 2021, https://tripnet.org/wp-content/uploads/2021/06/TRIP_Interstate_Report_June_2021.pdf.

125 Mark Sutton, "33 Key Cities Where Cycling Is Growing Its Modal Share," Cycling Industry News, June 24, 2020, https://cyclingindustry.news/five-key-cities-where-cycling-is-taking-modal-share-from-cars/; Peter Yeung, "Cars Are Vanishing from Paris," Reasons to be Cheerful, September 28, 2022, https://reasonstobecheerful.world/cars-are-vanishing-from-paris/.

126 Renate van der Zee, "How Amsterdam Became the Bicycle Capital of the World," The Guardian, Guardian News and Media, May 5, 2015, https://www.theguardian.com/cities/2015/may/05/amsterdam-bicycle-

Scenarios 2–4 may seem dramatic, many precedents show they are possible—and that the policies that enable them consistently become extremely popular once implemented.[127]

Finally, mode shifts and land use changes more dramatic than those modeled in even our most ambitious scenario have already occurred in the US—although in the opposite direction. Through urban renewal programs, the construction of the interstate highway system, subsidies for suburbanization, and other policies, the United States largely destroyed and rebuilt its cities in the mid-twentieth century in ways that created highly racialized urban geographies characterized by segregation, car dependency, and urban sprawl.[128] The injustices and damages wrought by this process have been immense, and the process is implicated not only in the climate crisis but an array of other major social and economic problems.[129] **Our most ambitious scenario would entail a near inversion of this transformation over a similar time horizon. Such an inversion could bring manifold social benefits—as well as reduce harms from minerals mining and likely speed up the timeline of decarbonization.**

All of our scenarios are built from data on currently existing transportation systems. They reflect realities already realized elsewhere in the world. The section "Building Decarbonization Pathways from Data on Global Transportation Systems" in the appendix presents extensive data from the United States and globally that were incorporated into these scenarios, details how the scenarios were built, and notes explicitly how parameters vary across scenarios.

capital-world-transport-cycling-kindermoord.

127 Andrew Kersley, "People Hate the Idea of Car-Free Cities—Until They Live in One," Wired UK, June 21, 2022, https://www.wired.co.uk/article/car-free-cities-opposition; Ido Vock, "How Anne Hidalgo's Anti-Car Policies Won Her Re-Election in Paris," New Statesman, June 29, 2020, https://www.newstatesman.com/world/2020/06/how-anne-hidalgos-anti-car-policies-won-her-re-election-paris; Nick Romeo, "How Oslo Learned to Fight Climate Change," New Yorker, May 4, 2022, https://www.newyorker.com/news/annals-of-a-warming-planet/how-oslo-learned-to-fight-climate-change; Sarah Wilson, "People Protested When This Capital City Went Car-Free. Now They Love It," Big Issue, August 15, 2022, https://www.bigissue.com/news/environment/people-protested-when-this-capital-city-went-car-free-now-they-love-it/.

128 The populations of major cities such as Philadelphia and St. Louis durably declined by 30 percent or 60 percent following these mid-century policies, according to historical decennial census data from the US Census Bureau, 1950–2000.
See also Jessica Trounstine, Segregation by Design: Local Politics and Inequality in American Cities (Cambridge: Cambridge University Press, 2019); Robert M. Fogelson, Downtown: Its Rise and Fall, 1880–1950 (New Haven, CT: Yale University Press, 2003); Kenneth T. Jackson, Crabgrass Frontier: The Suburbanization of the United States (Oxford University Press, 2012).

129 Freemark et al., "Toward a Green New Deal for Transportation."

LITHIUM DEMAND BY DECARBONIZED TRANSPORTATION SCENARIO

In this section, we estimate how much lithium would be required between 2020 and 2050 under each of the four transportation scenarios. First, we model new EV sales for passenger cars and buses that bridge the existing fleet to the futures envisioned for 2050. This requires data about historic sales and vehicle failure rates to understand what vehicles are on the road today and when they will need to be replaced. Then, for each new EV sold, we estimate material demand based on the battery size, lifetime, and chemistry.

Figure 9 illustrates our approach to estimate cumulative lithium demand, and the following sections explain the model, data, and assumptions.

EV Sales Forecast

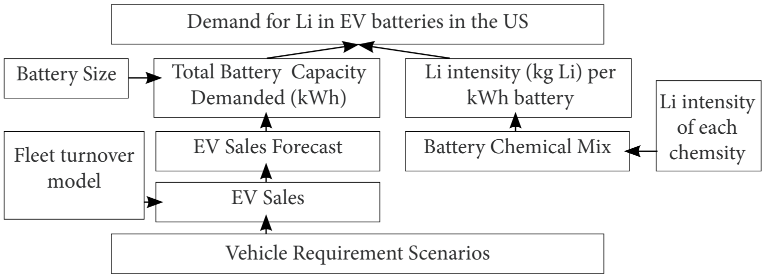

Figure 9. Modeling approach for estimating lithium demand from EVs in the US

The first step in estimating future EV sales is understanding the future vehicle stock requirements. In this model, historical EV stock and sales were drawn from the International Energy Agency Global EV Outlook, the Bureau of Transportation Statistics, and the School Bus Fleet website.[130] The future vehicle requirement estimates were calculated based on the 2050 vehicle requirements from the decarbonized transportation scenarios.[131] The historicaland future projections were then used to estimate total EV requirements between 2021 and 2049.[132] We combine these vehicle requirements with estimates of vehicle retirements over time to infer demand for EVs, which we assume to be equal to new vehicle sales. More information on vehicle sales and retirement modeling is available in the appendix to this report.

Average private vehicle lifetime is 16.6 years.[133] For this model, we assume an average vehicle lifetime of 15 years for privately owned passenger cars. Some batteries fail during their warranty period, meaning they are replaced before the vehicle is retired, which contributes to increased demand for new batteries. Based on recent measures to standardize and guarantee battery warranty periods, the model assumes as a base case that a failed battery will be replaced up to 8 years after a vehicle is sold (see the discussion on battery warranties in the appendix for more information). Large batteries may prove to have longer lifetimes than smaller batteries because they experience less cycling during use; but in this modeling, all batteries are expected to fail at similar rates. We also explored longer warranty periods of 10 and 12 years, though this has a very small effect on cumulative lithium demand.

Battery Capacity

Once vehicle sales over time are modeled, information on the size and chemistry of the battery packs in those vehicles is required to estimate lithium demand. The sales-weighted average battery capacity of a new EV in the United States has increased from about 35 kWh in 2012 to just over 70 kWh in 2021.[134] This means that the average new vehicle as significantly more energy storage capacity than earlier EV models. This average has remained nearly constant since 2018, indicating that average battery capacity may be leveling off somewhere between 70 and 75 kWh. Here, we use three different scenarios for modeling the future sales-weighted average battery capacity:

130 “Trends in Electric Light-Duty Vehicles – Global EV Outlook 2022 – Analysis,” n.d., International Energy Agency, https://www.iea.org/reports/global-ev-outlook-2022/trends-in-electric-light-duty-vehicles; “Bus Profile,” Bts.gov, 2022, https://www.bts.gov/content/bus-profile; Schoolbusfleet.com, 2022, https://www.schoolbusfleet.com/download?id=10131913&dl=1.

131 “Trends in Electric Light-Duty Vehicles – Global EV Outlook 2022 – Analysis.”

132 Historical and future projections were regressed on second- and third-order polynomials to estimate total EV requirements between 2021 and 2049. See David R. Keith, Samantha Houston, and Sergey Naumov, “Vehicle Fleet Turnover and the Future of Fuel Economy,” Environmental Research Letters 14, no. 2 (2019): 021001, https://doi.org/10.1088/1748-9326/aaf4d2.

133 Stacy Davis and Robert Boundy, Transportation Energy Data Book, Edition 40, Office of Scientific and Technical Information, 2022.

134 “EV-Volumes — The Electric Vehicle World Sales Database,” n.d., Ev-volumes.com, http://www.ev-volumes.com/datacenter.

- Small scenario: A future dominated by 35 kWh batteries, resulting in a sales-weighted average of 53.5 kWh.
- Medium scenario: A future dominated by 70 kWh batteries, with a sales-weighted average of 76.75 kWh.
- Large scenario: A future dominated by 150 kWh batteries, with a sales-weighted average of 122.5 kWh.

The small battery capacity was chosen based on early EV battery capacities like the first- and second-generation Nissan Leafs, and the large battery capacity was chosen based on recent electric light trucks like the Ford F-150 Lightning, the Rivian R1T, and the e-Hummer. Because the current battery capacity has held constant at just above 70 kWh, the medium battery scenario is treated as the most likely case. The capacity of battery packs alone, however, cannot determine their material intensity. Understanding the particular lithium-ion chemistry is also required.

Battery Cathode Chemistry

LIBs are often distinguished by their chemistry, which refers to the active materials in the cathode. The most common cathode chemistries for EVs are NMC (nickel manganese cobalt), NCA (nickel cobalt aluminum oxide), LFP (lithium phosphate), and LMO (lithium manganese pxide). NMC batteries are further differentiated by the ratio of nickel, manganese, and cobalt in the cathode respectively; for example, NMC 111 refers to a battery with an equal weight of nickel, manganese, and cobalt. The most common NMC chemistries are NMC 111, 523, 622, and 811, with the market trending toward higher nickel concentrations (e.g., NMC 622 and NMC 811) to reduce the amount of cobalt and lithium required.[135]

Since 2018, NCA has represented more than half of the share of batteries in new EV sales in the United States, a larger share compared to other countries. This is mainly because Tesla has the highest EV sales in the United States and uses almost exclusively NCA batteries. In this study we assume that passenger EV batteries will be 50 percent NCA and 50 percent NMC 811 into the future, and e-bus batteries will be 50 percent LFP and 50 percent NMC 811, reflecting two popular e-bus models from makers BYD and Proterra.

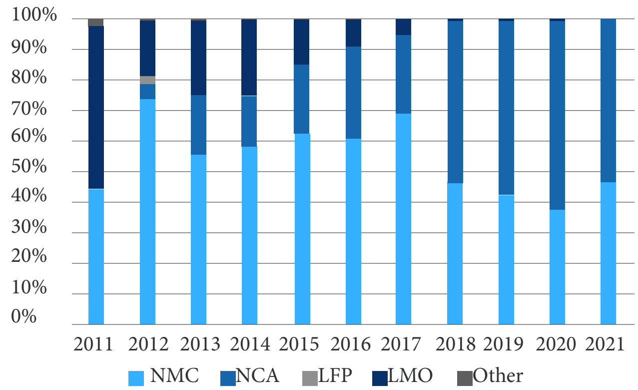

Figure 10. Battery chemistry types in new light-duty EV sales in the United States (2011-2021)[137]

Bus modeling[136]

In addition to the light-duty vehicle sector, battery-electric buses (e-buses) will be an important part of battery demand for future transportation scenarios. Two types of buses are widely used in the US: school buses and transit buses.

We use the same approach for determining bus sales as for light-duty vehicles, whereby the final bus requirement estimated in the different decarbonization strategies is used along with historical bus stock data to estimate the US bus stock between 2010 and 2050.[137] A fleet turnover model is used to estimate bus retirement. Transit and school bus fleets are modeled separately with respect to fleet size and fleet turnover. Transit buses are typically purchased and overhauled based on available federal funding provided in 7-year cycles. Transit buses also accrue mileage much faster than school buses and undergo what is known as a seven-year midlife overhaul during which a bus's battery pack is assumed to need replacement.[138] Thus the fleet turnover model assumes a fixed 14-year transit bus lifetime with a seven-year midlife overhaul that includes full battery replacement. Unlike for light-duty vehicles, we do not model lifetime stochastically, or statistically determined, because of a lack of data on bus survival rates. We assume all e-buses include a 450 kWh hour battery pack based on popular

135 Because of their higher energy density, NCA and NMC 811 contain the smallest amount of lithium for every kWh of energy stored–about 0.1 kg/kWh. NMC 111 has the highest lithium requirement of the common cathode chemistries at 0.14 kg/kWh. LTO, LMO, and LFP are all used in the US but at much lower rates than NMC and NCA. LMO and LFP require 0.106 kg/kWh and 0.095 kg/kWh, respectively. See Figure 31 [Relative mineral content in various LIB chemistries] in the appendix.

136 "EV-Volumes—The Electric Vehicle World Sales Database."

137 "Transit Profile," Bureau of Transportation Statistics, n.d. https://www.bts.gov/content/transit-profile-0.

138 Hanjiro Ambrose, "Exploring the Costs of Electrification for California's Transit Agencies," University of California, Institute of Transportation Studies, 2017, https://doi.org/10.7922/G2PZ570Z.

e-bus models from Proterra and BYD.[139] School buses are, on average, much older than transit buses. They are used for many more years because they operate few routes per day, accruing mileage more slowly than active transit buses. Based on personal communication with a school bus manufacturer, we assume a bus lifetime of 20 years. Given the low mileage accrual, no battery replacements are modeled for school buses.

Recycling

Recycling could reduce the need for new lithium extraction significantly, and materials from recycled batteries may even perform better than virgin materials.[140] This report explores the potential for recycling to meet future material demand under a future where 100 percent of EV batteries are collected for recycling, and recycling processes achieve 98 percent recovery of target materials, including lithium.[141] This represents a best-case scenario for recycling; in reality, the collection and recycling rates of EV batteries are not well characterized, which presents a challenge for both estimating the current and future rates of recycling and for material recovery.[142] In addition, recycling processes do not necessarily cover all materials. The choice of which materials to recover is an economic one, and is driven by the value of each material. Historically, it has been cheaper to mine new lithium than recycle it, making the recovery of lithium less attractive to recyclers.[143]

Given the projected growth in EV sales and the long lives of vehicles, it will be decades until recycling can meet a substantial fraction of global demand.[144] Additionally, used EV batteries can be repurposed for energy grid storage, as they still have significant capacity even at the car's end-of-life. On a life cycle basis, reuse reduces burdens relative to recycling and production of new batteries, even considering the deteriorating performance of batteries over time.[145] However, extending a battery's use phase via repurposing may be somewhat in tension with goals for generating recycled material, given that an EV battery that is repurposed for another use is one that is not being recycled for new battery production.

To maximize battery collection and material recovery, the EU has proposed new battery regulation around circular economy principles,[146] and China has incentives for making batteries from recycled materials, among other industrial policies encouraging domestic battery recycling.[147] The proposed EU regulation includes extended producer responsibility for end-of-life batteries, and specifies minimum levels of recycled content for certain battery materials starting in 2030 (12 percent for cobalt, 4 percent for lithium, and 4 percent for nickel). In other words, 12 percent of the cobalt used to manufacture industrial batteries will need to come from recycling.[148]

Modeled Scenarios

To understand the range of possible demand for lithium,

139 "A Look at the Listed Electric Bus Sector as Biden Moves to Electrify America," Seeking Alpha, March 18, 2021, https://seekingalpha.com/article/4414950-look-listed-electric-bus-sector-biden-moves-to-electrify-america; For ProTerra ZX5 35-foot battery electric transit bus platform specifications, see https://www.proterra.com/wp-content/uploads/2022/09/SPEC_35_001_Q4_2022_V1_09_01_22.pdf.

140 Xiaotu Ma, Mengyuan Chen, Zhangfeng Zheng, Dennis Bullen, Jun Wang, Chloe Harrison, Eric Gratz, et al., "Recycled Cathode Materials Enabled Superior Performance for Lithium-Ion Batteries," Joule 5, no. 11 (2021): 2955–70, https://doi.org/10.1016/j.joule.2021.09.005.

141 Jessica Dunn, Margaret Slattery, Alissa Kendall, Hanjiro Ambrose, and Shuhan Shen, "Circularity of Lithium-Ion Battery Materials in Electric Vehicles," Environmental Science & Technology 55, no. 8 (2021): 5189–98, https://doi.org/10.1021/acs.est.0c07030.

142 Yanyan Zhao, Oliver Pohl, Anand I. Bhatt, Gavin E. Collis, Peter J. Mahon, Thomas Rüther, and Anthony F. Hollenkamp, "A Review on Battery Market Trends, Second-Life Reuse, and Recycling," Sustainable Chemistry 2, no. 1 (2021): 167–205, https://doi.org/10.3390/suschem2010011.

143 Davide Castelvecchi, "Electric Cars and Batteries: How Will the World Produce Enough?," Nature 596, no. 7872 (2021): 336–39, https://doi.org/10.1038/d41586-021-02222-1.

144 Dunn et al., "Circularity of Lithium-Ion Battery Materials in Electric Vehicles."

145 Jessica Dunn, Alissa Kendall, and Margaret Slattery, "Electric Vehicle Lithium-Ion Battery Recycled Content Standards for the US—Targets, Costs, and Environmental Impacts," Resources, Conservation, and Recycling 185 (2022): 106488, https://doi.org/10.1016/j.resconrec.2022.106488.

146 Elsa Dominish, Nick Florin, and Rachael Wakefield-Rann, "Reducing New Mining for Electric Vehicle Battery Metals: Responsible Sourcing Through Demand Reduction Strategies and Recycling," Earthworks, April 27, 2021, https://earthworks.org/resources/recycle-don't-mine/.

147 Castelvecchi, "Electric Cars and Batteries: How Will the World Produce Enough?"

148 "Proposal for a Regulation of the European Parliament and the Council Concerning Batteries and Waste Batteries, Repealing Directive 2006/66/EC and Amending Regulation (EU) No 2019/1020," edited by the European Commission, Brussels, Belgium, 2020, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020PC0798.

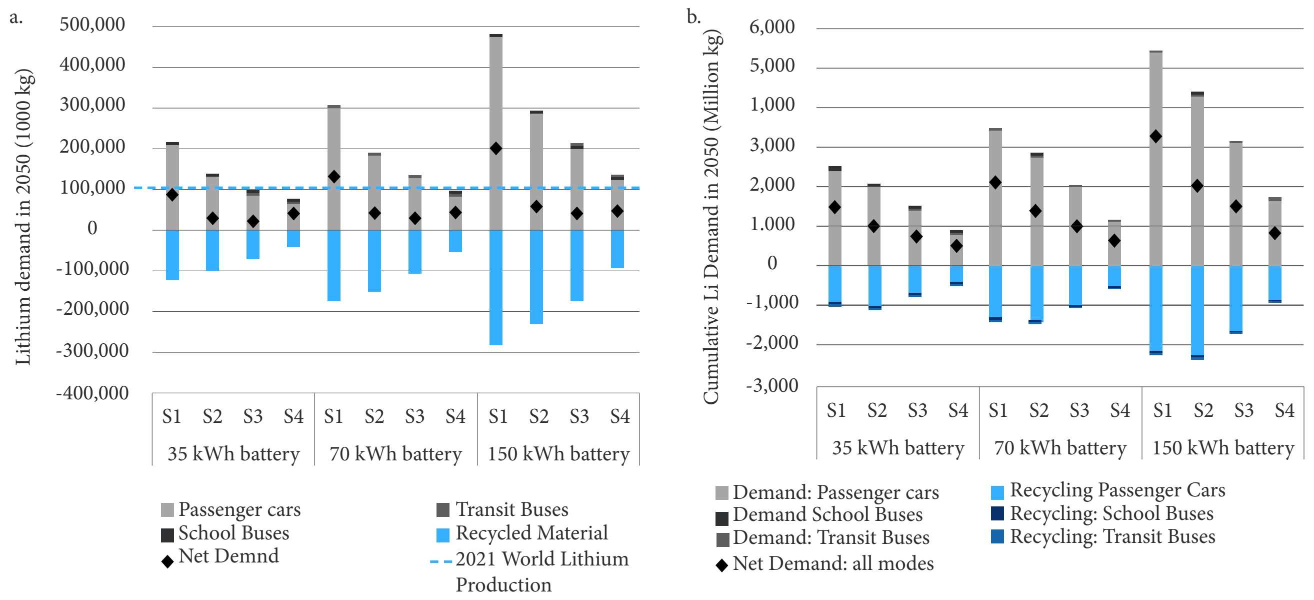

Figure 12. a) US EV battery lithium demand, recycled material potential, and potential net demand in 2050 for scenarios (S1, S2, S3, and S4) with an 8-year battery warranty period in the year 2050. b) US EV cumulative lithium demand, cumulative recycled material potential, and potential net demand, 2010–2050.

we use a scenario analysis approach that combines possible decarbonization pathways, possible vehicle design choices, possible battery warranty requirements, and worst- and best-case recycling futures. For buses, only the decarbonization and recycling scenarios apply, since battery size is fixed and replacement rates are independent of warranty periods. Figure 11 describes the scenarios modeled.

Decarbonization Pathway	B: Base Case	L: Lite	M: Moderate	A: Ambitious
Light-Duty EV Average Battery Size	S: Small	M: Medium	L: Large	
Light-Duty EV Warranty Period	8: 8 Year	10: 10 Year	12: 12 Year	
Recycling	R: Recycling credit	N: No recycling credit		

Figure 11. Scenarios included in the assessment.

In the absence of intervention, the most likely scenario seems to be the base case, with medium (76.75 kWh) average battery capacity and an 8-year warranty period. For recycling, there is significant uncertainty in the rate of battery collection for recycling; moreover, there is significant uncertainty in whether lithium will be recovered. Historically, only high-value metals like cobalt and nickel were targeted for recovery, with lithium retained in the slag generated from the process. However, with increasing lithium prices and improved recycling technology, high rates of recovery could occur. As a result, we explore two scenarios at the extreme—one where no lithium recovery occurs, and another with 98 percent recovery of lithium assuming 100 percent collection of retired batteries. Complete scenario results are shown in the appendix, Tables 9-14.

Lithium Demand Results

The results demonstrate that both increasing the ease and availability of other forms of transport and changing EV design (i.e., reducing battery size) can significantly influence cumulative demand for LIBs and the lithium required to produce them. When comparing the lithium demand of different transportation futures to the base case, there is an 18 percent, 41 percent, and 66 percent reduction for Scenarios 2, 3, and 4, respectively.[149] There is a 29 percent reduction in cumulative lithium requirement for the base case when comparing the small battery scenario to the medium scenario.[150] Conversely, there is a 56 percent increase in cumulative lithium demand when comparing the same base case to the large battery scenario with an eight-year warranty. Extending the warranty period has a smaller effect on lithium demand compared to battery size and transportation future. When comparing the cumulative lithium requirement of the medium battery scenario and the common eight-year battery warranty to a 10- and 12-year warranty, there is a 1.3 percent and 4.1 percent increase in lithium requirement, respectively. These results suggest that reducing demand for passenger vehicles, densifying urban areas, and maintaining or reducing battery capacity are the most effective pathways to reducing future lithium demand. Passenger cars accounted for the greatest demand for lithium because they are the dominant mode choice in

149 Assuming a medium sales-weighted average battery capacity (76.75 kWh) with an 8-year warranty period.

150 Assuming an 8-year warranty period.

Table 3. Percent change in cumulative lithium demand as a function of battery size and decarbonize transportation future

Battery Capacity Scenario	Future Scenario	Percent Change in Cumulative Li Demand	Percent Change in 2050 Li Demand
Small	S1	-29%	-29%
	S2	-40%	-56%
	S3	-57%	-68%
	S4	-74%	-74%
Medium	S1	0%	0%
	S2	-18%	-38%
	S3	-41%	-55%
	S4	-66%	-67%
Large	S1	56%	58%
	S2	26%	-4%
	S3	-10%	-31%
	S4	-50%	-55%

Table 4. Percent change in lithium demand as a function of warranty period and decarbonized transportation future

Battery Warranty Period	Future Scenario	Percent Change in Cumulative Li Demand	Percent Change in 2050 Li Demand
8 Year	S1	0%	0%
	S2	-18%	-56%
	S3	-41%	-68%
	S4	-66%	-74%
10 Year	S1	1%	2%
	S2	-17%	-37%
	S3	-40%	-54%
	S4	-66%	-67
12 Year	S1	4%	6%
	S2	-14%	-34%
	S3	-38%	-52%
	S4	-64%	-66%

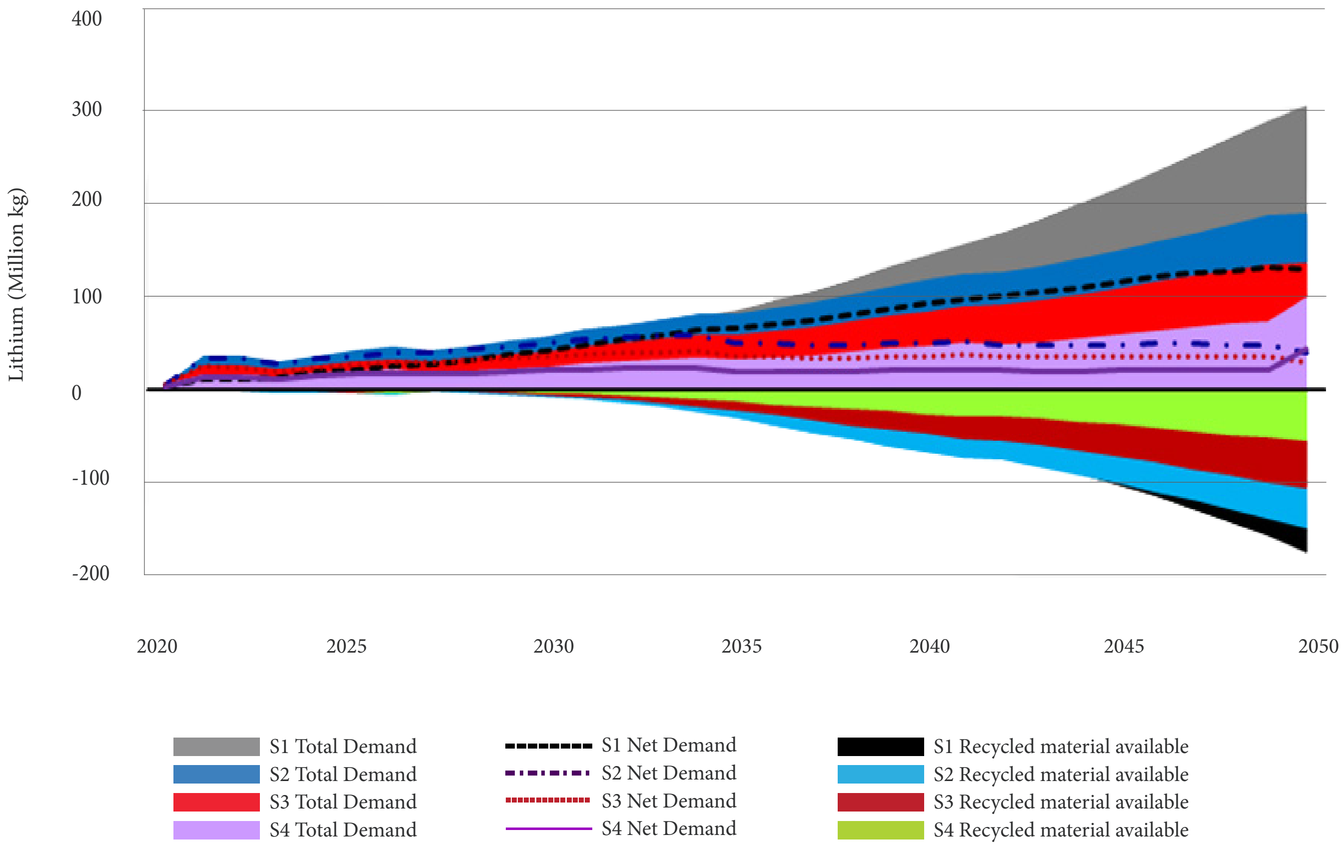

Figure 13. Lithium demand under decarbonized transportation futures assuming medium battery capacity, 8 year warranty period and 98 percent recovery of all lithium from retired batteries in the year in which they retire.

every transportation future scenario modeled. Although buses have much larger batteries in each vehicle, their vehicle numbers are low enough that they still contribute only a small amount of demand, as illustrated in Figures 12 a and b. [See Figure 4]

Additional scenario results are shown in Tables 3 and 4. In both tables, results are reported as the percent differences using the base case decarbonized transportation future with the medium battery scenario, and eight-year warranty as the reference scenario. These tables show that transportation future is by far the most influential determinant of future lithium demand, with demand falling by two-thirds in the ambitious case. Average battery capacity is also important but less influential in determining future mineral demand. Warranty period has little effect on lithium demand.

Recycling under ideal conditions (meaning perfect collection systems with 98 percent material recovery and batteries that move straight to recycling after they are retired) could cumulatively provide about 38 percent of new lithium demand for batteries under the modeled scenario. Figure 13 shows the lithium material demanded, the maximum possible supply of recovered lithium via recycling, and the net demand (i.e., demand that cannot be met by recycled lithium) over time. Despite the unrealistic battery collection rates and lithium recovery rates, recycling still cannot meet even 50 percent of demand in 2050, indicating that recycling, while important, cannot in the coming decades solve the problem of lithium demand from EV batteries. Reducing demand for lithium in the first place via reducing vehicle ownership is still more effective at reducing demand for new lithium compared to overly optimistic conditions for future recycling. However, recycling should be pursued regardless of the decarbonized transportation future that we find ourselves in, because at any level of EV deployment, recycling reduces the demand for new lithium extraction.[151]

Perhaps more easily contextualized with respect to current lithium demand and supply are estimates of annual lithium demanded for these scenarios. Figure 12a shows the annual demand for lithium in 2050 required to meet US passenger transportation demand in personal vehicles and buses. **Note that in all but Scenario 4, US**

151 For a longer discussion of recycling's potential to replace new mining, see Dominish et al.,"Reducing New Mining for Electric Vehicle Battery Metals."

demand will exceed current total global production, and global production will need to meet demand for all markets, including China and Europe, which are currently larger than the United States. If today's conditions are projected to 2050, US EV demand for lithium alone would require triple the amount of lithium produced today for the global market. For reference, the United States comprised 12 percent of the global EV market in 2021.[152] If the upper boundary of recycling and recovery is achieved, 27 percent of lithium demand in 2050 could be met with recovered materials (see Table 12 in the appendix). This would substantially reduce demand, but would still mean that US EV demand would need more than double the total amount of lithium produced annually in the world today.

Limitations for Lithium Demand Modeling

There are significant interaction effects between battery size and battery lifetime (i.e., durability) that are not considered in the modeling of future lithium demand. Bigger batteries, all else equal, will last longer than small ones because they are cycled less frequently. This could either mean that we are underestimating the lifetime of EVs with larger batteries and thus overestimating the demand for new vehicles and batteries; or we are overestimating the lifetime of small EV batteries and underestimating replacement requirements.

A number of omissions from recycling and circularity estimates are also important. First, the United States supplies used vehicles to external markets, largely in lower- and middle-income countries, around the world. In this modeling, we assume all vehicles retired from US roads are retained within the US boundaries. Similarly, implicit in our circularity estimates are that US EV batteries will be recycled and that material will be incorporated into new EV batteries also sold in the United States.

152 Based on pure EV sales (excluding PHEVs). See "Trends in Electric Light-Duty Vehicles – Global EV Outlook 2022 – Analysis."

> **"The results demonstrate that both increasing the ease and availability of other forms of transport and changing EV design (i.e., reducing battery size) can significantly influence cumulative demand for LIBs and the lithium required to produce them."**

CONCLUSION

A transportation strategy that foregrounds mass transit, cycling, and walkability—combined with a circular economy approach to raw material recovery and reuse—implies an overall reduction in new lithium mining and localized vehicle pollution, improvements in transportation equity, and a hastening of urgent planetary decarbonization. By reducing lithium demand relative to the most alarming forecasts, such a pathway provides a clear alternative to prevailing transportation scenarios, which rely on fast-tracking new mines, intensifying environmental pressures on landscapes subject to mining, destroying Indigenous lands and livelihoods, or increasing pressure on globally fraught supply chains in order to power an expansive, electrified car fleet. There are tools available now, and at multiple scales of government, to lower demand for lithium and move toward closing the lithium supply gap while also reducing emissions and advancing more climate-ready, healthy, and safe systems of mobility in the United States.

Our findings show that reducing dependence on private vehicles, densifying low-density suburbs while allowing more people to live in existing high-density urban spaces, and improving EV efficiency and reducing battery sizes are the most effective pathways to reducing future lithium demand.

Reducing US car dependency also presents new opportunities to address the long-standing harms and exacerbations of social inequity created by a built environment that prioritizes personal vehicles over communities, with negative consequences to quality of life and environmental health. State and federal governments can increase investment in and access to public and active transit options, while continuing to support the transition of the ICE fleet to EVs. In cities, governments can promote transit options like bicycling and walking by increasing the availability and safety of bike lanes, sidewalks, and car-free streets; subsidizing bikes and e-bikes; facilitating car-share programs as an alternative to individual car ownership; and providing low- or no-cost options for bike shares. Transit authorities and Amtrak should be encouraged and/or legislated to run higher-frequency, lower-cost regional rail to enhance mobility and replace car trips.[153] These strategies will have to be supplemented with decreased spatial and financial subsidies for private vehicles: on-street parking spaces should be curbed; free parking should be removed; additional charges should be levied for oversized vehicles, including personal trucks and SUVs; and congestion charges, car-free, and car-light city centers should be implemented.[154] Meanwhile, building codes, zoning, and land-use laws will need to be reformed to facilitate new housing in which residents will be able to live and have families without depending on cars for their daily transportation needs. Many other policies can and should be implemented to bring the United States toward a better, safer, healthier, and less lithium-intensive transportation system, while structuring the transition in such a way as to maximally reduce social and racial inequities. A full assessment of such policies is outside the scope of this report, although the preceding discussion, and the earlier "Green New Deal for Transportation" report from the Climate and Community Project, lays out some key strategies.[155]

The design of future vehicles is also important. Interrupting the trend for ever-larger vehicles—which require ever-bigger batteries—is a key lever for reducing demand in our modeling. Reversing this trend is also monumentally important for decarbonizing the transportation sector and reducing traffic deaths. Other research has found that more stringent energy-efficiency standards for EVs is necessary to keep climate change below 1.5–2°C of warming.[156] And the trend of increased vehicle size is a major contributor to the ever-increasing number of deaths from traffic crashes in the United States.[157]

A decade ago, the EPA had to harmonize fuel economy and greenhouse gas standards for vehicle tailpipes. A

153 A program in Germany that offered low-cost flat-fare monthly regional rail tickets proved immensely popular, providing stable travel options during a period of quickly increasing gas prices and decreasing carbon emissions. See "Five Ways a Groundbreaking €9 Rail Pass Changed Germany," Euronews, September 20, 2022, https://www.euronews.com/my-europe/2022/09/20/five-ways-a-groundbreaking-9-rail-pass-changed-germany; Jake Blumgart, "Taking the 'Commuter' Out of America's Rail Systems," Governing, April 22, 2021, https://www.governing.com/now/taking-the-commuter-out-of-americas-rail-systems.

154 Kuss, Paula, and Kimberly A. Nicholas. 2022. "A Dozen Effective Interventions to Reduce Car Use in European Cities: Lessons Learned from a Meta-Analysis and Transition Management." Case Studies on Transport Policy 10 (3): 1494–1513. https://doi.org/10.1016/j.cstp.2022.02.001.

155 Freemark et al., "Toward a Green New Deal for Transportation."

156 Milovanoff et al., "Electrification of Light-Duty Vehicle Fleet Alone Will Not Meet Mitigation Targets."

157 Diana Ionescu, "Bigger Vehicles, Blindspots Contributing to More Pedestrian Deaths," Planetizen, March 18, 2022, https://www.planetizen.com/news/2022/03/116570-bigger-vehicles-blindspots-contributing-more-pedestrian-deaths; David Zipper, "The Car Safety Feature That Kills the Other Guy," Slate, November 7, 2022, https://slate.com/business/2022/11/suv-size-truck-bloat-pedestrian-deaths.html\; B. Claus and L. Warlop, "The Car Cushion Hypothesis: Bigger Cars Lead to More Risk Taking-Evidence from Behavioural Data," Journal of Consumer Policy 45, no. 2 (2022): 331–42, https://doi.org/10.1007/s10603-022-09511-w.

transformation in conceptions of vehicle efficiency and environmental impact is needed—one that considers the impacts of vehicle production and not just vehicle operation. It is necessary to policy that considers the impact of vehicle production, whether through the embedding of emissions or impacts from production in current corporate average fuel economy (CAFE) standards,[158] or other measures that consider the entire environmental and social burden of vehicle life cycles starting with the mines at the beginning of supply chains. Such policies could contribute to reducing material demand in decarbonized transportation futures. **An exclusive focus on greenhouse gas emissions and vehicle efficiency could lead to burden shifting from one impact and particularly affected communities to a different impact affecting different communities.** More comprehensive indicators of social and environmental impacts embedded in policy could prevent this.

Recycling and recovery of lithium is another important measure. Given the economics of lithium recovery, policy intervention is likely required to ensure that resource recovery is not purely driven by price. The EU has proposed recycled content standards for future batteries that can improve the economic conditions for material recovery, particularly for lithium, which otherwise may not be as attractive as nickel, cobalt, and other higher-value metals. Other policies such as extended producer responsibility with additional conditions for battery handling and material recovery could be effective as well.

As demonstrated by the case studies featured in this report, the frontlines of mining must be central to US transportation decarbonization scenarios. This means enforcing community rights, expanding and implementing environmental regulations, adopting more democratic decision-making processes, and considering "no-go" zones and/or moratoriums on mining in water-vulnerable and/or culturally sensitive landscapes. These principles must extend beyond US borders, by incorporating supply chain justice into trade agreements to ensure imported materials are governed by high standards for labor, human, and Indigenous rights, in addition to environmental regulations and emissions standards.

A powerful complement to these governance reforms at the sites of extraction is reducing overall demand, which in turn reduces the scramble for resources and protects communities, landscapes, and ecosystems from damage that in many cases is irreversible. **For these reasons, we advocate for a holistic, end-to-end supply chain approach to globally just transportation, which considers the structural drivers of mining demand and envisions an ambitious transformation of this sector.**

The transition to electrified transportation is essential for decarbonization. This transition will be both speedier and more globally just if the United States reduces car dependency, expands mass transit, and thereby reduces the lithium intensity of the electrified transportation system. Achieving this future is possible, with levers ranging from mass transit policy, to land use and zoning decisions, to regulations regarding battery size and car warranties, to streetscape planning that incorporates walkability and cycling safety. These decisions are made by elected and appointed officials in municipal, state, and federal governments. We understand the realities of US congressional gridlock and partisan polarization: for exactly this reason, we construct a wide range of multifaceted transportation futures, with many points for policy and community intervention. **This report intends to empower people and policymakers across the country with the arguments, evidence, and proposals they need to advocate for a maximally just transportation future.**

158 Alissa Kendall and Lindsay Price, "Incorporating Time-Corrected Life Cycle Greenhouse Gas Emissions in Vehicle Regulations," Environmental Science & Technology 46, no. 5 (2012): 2557–63, https://doi.org/10.1021/es203098j.

APPENDICES

The next section discusses how these scenarios were constructed from data on global transportation scenarios. The following section, "Decarbonized Mobility Scenarios," discusses how each scenario was built from sets of parameters and notes explicitly how these parameters vary across scenarios.

Building Decarbonization Pathways from Data on Global Transportation Systems

The decarbonization of global transportation systems is already underway. Different stages and approaches to the transition can be found in existing global variation in transportation systems, and applied to US cities to demonstrate possible future pathways. Climate and transportation researchers have illustrated the relationships between transportation systems, built environments, and emissions reductions. For example, allowing more people to live in places associated with lower car use is a vastly effective tool in reducing energy use and greenhouse gas emissions.[159] This section takes stock of existing transportation systems globally to help determine a set of achievable transportation futures.

Overview of Vehicle Requirements Modeling

Figure 14 shows how vehicle requirements were modeled for our four decarbonized mobility scenarios. In this plot, [blue] shows a step of calculation or a static set of projections, while [green] show parameters that vary across the models.

The total population over time, which does not vary across the scenarios, is allocated to rural areas, low-density urban areas, and medium-density urban areas, which we will refer to as density classes. A set of parameters for mode share (the proportion of trips occurring by different travel modes—private vehicle, public transit, or active transit) is applied. For each scenario, projected mode shares are used for each separate density class; that is, each scenario applies a set of parameters for how people tend to get around in rural, low-density urban, and medium-density urban areas.

From the population living at different density classes, and the mode shares by density classes, we estimate the

159 Newman and Kenworthy, "Gasoline Consumption and Cities Revisited"; Newman and Kenworthy, The End of Automobile Dependence; Newman, "Cool Planning"; "U.S. Cities Factsheet"; Jones, Wheeler, and Kammen, "Carbon Footprint Planning."

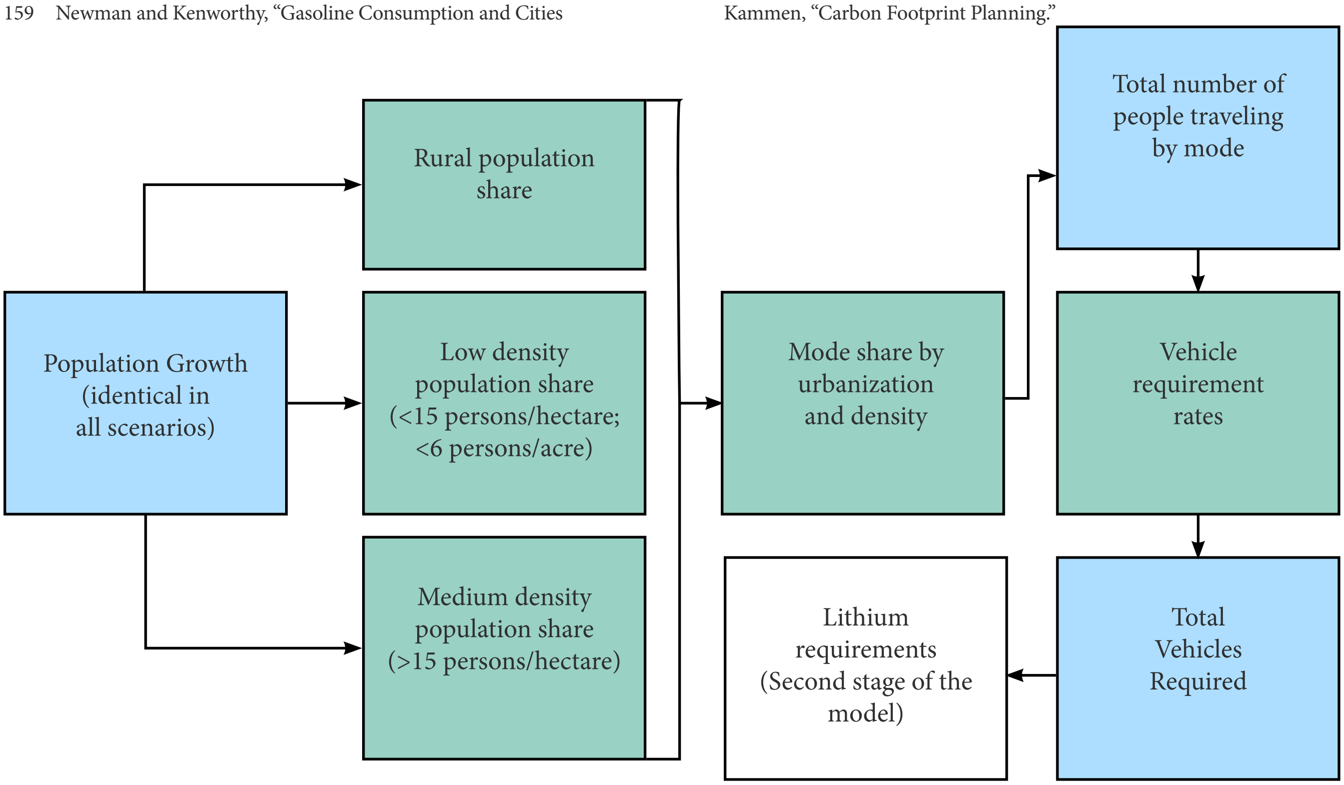

Figure 14: Vehicle Requirement Modeling Flowchart

Table 5: Vehicle Requirements and Parameters across the Four Decarbonized Mobility Scenarios

Scenario	Urbanization/ Density Class	Population (%)	Active transit mode share (%)	Car mode share (%)	Other mode share (%)	Public transit share (%)	Car requirements (millions)	Transit bus vehicle requirements (millions)
Scenario 1	Rural	19.02	2.85	93.31	1.28	2.56	60.75	0.01
	Low density	62.14	3.22	88.21	4.97	3.60	187.58	0.04
	Medium density	18.84	4.59	75.98	5.49	13.95	48.99	0.04
Scenario 2	Rural	19.02	2.85	93.31	1.28	2.56	60.75	0.01
	Low density	62.14	28.10	59.70	1.60	10.60	126.96	0.11
	Medium density	18.84	37.21	42.51	0.08	20.14	27.41	0.06
Scenario 3	Rural	19.00	2.85	93.31	1.28	2.56	60.68	0.01
	Low density	31.00	28.10	59.70	1.60	10.60	43.19	0.05
	Medium density	50.00	37.21	42.51	0.08	20.14	49.60	0.15
Scenario 4	Rural	15.00	5.00	90.00	0.00	5.00	46.20	0.01
	Low density	10.00	25.00	60.00	0.00	15.00	9.33	0.02
	Medium density	75.00	40.00	20.00	0.00	40.00	23.34	0.37

total number of people traveling primarily by different travel modes. A final set of parameters—the rate at which trips occurring by a given mode of transportation leads to vehicle requirements—allows us to estimate the total vehicles required in each scenario, which finally feeds into the second stage of the model that moves from vehicle to lithium requirements. For the modeling in this report, we only explicitly model light-duty passenger vehicles (cars, SUVs, and light trucks) and buses, including school buses. This is due to the high lithium requirements of these vehicles, compared to light and heavy passenger rail, bicycles, e-bikes, and other forms of micromobility.[160]

This appendix will first lay out how each scenario was quantitatively defined and the vehicle requirements for each scenario. It then will describe how the parameters were determined based on data from global transportation systems, and then discuss the structure of the model in more detail.

160 See Figure [4]: While e-bikes and other forms of micromobility do require some lithium, each e-bike would require about 1/400th the amount of a small electric car and less than 1/1000th of a large SUV or EV truck.

The Four Decarbonized Mobility Scenarios

Table 5 shows the parameters used in the four decarbonization scenarios. For example, in Scenario 1, 19 percent of the population lives in rural areas, and 93 percent of that population will travel primarily by car. Based on the vehicle requirements rate in that scenario, 60.75 million cars are required to serve the mobility needs of that portion of the population in that scenario.

The columns that define parameters are colored in green, to correspond with the model flowchart. Mode share percentages shown in this table refer to percent of trips. The two columns showing total vehicle requirements by type are shown in blue.

Because school buses were not modeled as a function of mode share across density classes, they have different units in the table. In Scenarios 1–3, school bus requirements were estimated from scaling the current stock of school buses with population

Table 6. Parameters for vehicle requirement rates by type of vehicle. Vehicle requirement rates for cars remains at 880 in rural areas in all scenarios.

Vehicle Requirement Rate	Scenarios 1 & 2	Scenario 3	Scenario 4
Cars (per thousand persons traveling primarily by car)	880	600*	400*
Transit buses (per million persons traveling primarily by public transit)	4,400	3,800	3,200
School buses (total, thousands)	560	560	**480**

growth; in Scenario 4, school bus requirements were decreased somewhat to reflect the likelihood that denser living and less car traffic would allow school buses to operate more efficiently.

The tables show how the models were parameterized, and how total vehicle requirements of different decarbonized mobility require drastically different numbers of vehicles. Table 5 also shows how vehicle requirements break down by rural and low- and medium-density places.

Data

To formulate the parameters used in the different decarbonized mobility scenarios, we incorporate three primary datasets to understand how aspects of transportation systems vary globally and impact one another:

- International Association of Public Transport (UITP) 2020 Mobility in Cities Database (MCD)[161]
- Deloitte City Mobility Index (DCMI) 2020/2018 data [162]
- US Census Bureau American Community Survey (ACS) 2019 data (5-year estimates)

The first two are international datasets. UITP MCD data build upon a decades-long effort to develop standardized, comparable transportation and urban characteristics for a selection of global cities.[163] We use the 2020 edition of this data, which reflects characteristics from 2012.

The DCMI data were collected from city-level reports from the consulting company Deloitte that include information on population density and mode share. A different selection of cities was available for the years 2018 and 2020, and data from the two years are combined for this report to provide a richer cross-sectional picture.

We compare results from these two datasets to check the robustness of the relationships we examine, but as a result of differences in time period, data collection approaches, and different areal definitions (such as urbanized area or metro area), the findings across the two different data sources do not exactly match.

The ACS data from the US Census Bureau is recent, are high quality, and allow comparison between places, but only include information within the United States.

Together, the three datasets provide a rich, relatively consistent picture of how the fundamental characteristics of transportation systems vary by place and help determine one another.

Importantly, while UITP and DCMI data estimate mode shares for all trips, ACS data estimate mode shares for work commutes. We use these commute mode shares as proxies for total mode shares when using ACS data. While

161 Mobility in Cities Database." n.d. UITP. https://www.uitp.org/publications/mobility-in-cities-database/.

162 "The 2020 Deloitte City Mobility Index." n.d. Deloitte.com. https://www2.deloitte.com/content/dam/insights/us/articles/4331_Deloitte-City-Mobility-Index/2020/DCMI_Methodology_2020_WEB.pdf.

163 Jeffrey R. Kenworthy, "The Good, the Bad and the Ugly in Urban Transport: Comparing Global Cities for Dependence on the Automobile," Methods for Sustainability Research, July 28, 2017, 46–62, https://doi.org/10.4337/9781786432735.00012.

commute shares are not perfect proxies for total trips—they will likely overstate trips occurring by public transit and understate trips happening by active transit—they represent the best data with complete coverage of US urban areas available. Comparison of ACS and DCMI data in urban areas covered by DCMI data shows that commute share (from ACS) tends to have car shares 3–5 percentage points higher than trip share (from DCMI). This suggests that the commute share data we use in Scenario 1 may slightly overstate the proportion of trips currently happening by car; this would make the mode shifts in scenarios 2–4 slightly less substantial than otherwise.

Additionally, all datasets tend to use "urbanized data" as the areal definition.[164] The UITP MCD data will sometimes include a broader analysis area, but includes a value for "urban" population density, which uses only the developed area to calculate density; we use this value for population density when using the UITP MCD data. The areal definitions across datasets and countries within international datasets are therefore relatively consistent and can allow meaningful comparisons, although there will still be noise arising from differing regional and national practices in defining urban areas.

Our analysis draws most heavily upon ACS data for analysis of existing conditions in US cities and most heavily on UITP MCD data to draw international comparisons and determine realistic transportation and urban density scenarios. The Deloitte data are used to supplement the picture from the UITP MCD data and establish that central relationships are consistent across datasets.

Finally, data from the US Department of Energy (DOE) and the World Resources Institute (WRI) are used to provide information on the number of cars, transit buses, and school buses currently in the United States, which are used to estimate future vehicle needs, supplying the parameters for vehicle requirements rates used in Scenarios 1 and 2.[165]

164 In the United States, urbanized areas omit less developed land and open space within a metropolitan area. "2010 Census Urban and Rural Classification and Urban Area Criteria," United States Census Bureau, October 28, 2021, https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-rural/2010-urban-rural.html.

165 Because one data point was used from the US Department of Energy and the World Resources Institute respectively, these sources are not included as "primary" data sources; Davis and Boundy, Transportation Energy Data Book, Edition 40; Lazer and Freehafer, "Dataset of Electric School Bus Adoption in the United States."

Density Classes and Transportation

The logic of our model starts with the robust and durable finding— first highlighted in 1989— that urban density corresponds with energy intensity of the transportation system.[166] The less dense a city is, the more energy will be required per person for transportation, and vice-versa.

This insight was first noted by transportation and sustainability researchers Peter Newman and Jeffrey Kenworthy. These researchers noted various thresholds of population density at which different modes of transportation will predominate. In their schema, in urban areas below 35 persons/hectare (ha), cars predominate; between 35 and 50 persons/ha, public transit predominates; at higher densities, walking predominates. It is notable that some of this data includes areas with a huge range of income levels.

However, UITP data show that car usage can drop off dramatically at densities lower than the 35 or 50 persons/ha thresholds in Newman and Kenworthy's classifications. Additionally, because of the high level of suburbanization and low densities in most US urbanized areas, very few areas currently approach either of these thresholds. To build mobility scenarios, we consider how the future US population may live at different population densities and levels of urbanization. For the reasons noted, we use different density levels than those used in Newman and Kenworthy. These urbanization/density classes are used here:

- Rural (outside of urbanized areas)
- Low-density urban areas (<15 persons/ha)
- Medium-density urban areas (>15 persons/ha)

We use definitions of urban areas from the US Census Bureau from 2019.

We use the terminology of low and medium densities to describe these thresholds because even the medium-density typology is dramatically lower than many other global cities. None of our decarbonization scenarios require any US urban areas to reach higher levels of density than the top threshold of 15 persons/ha. Realizing higher population densities in some cities would likely be beneficial only from most ecological, social, or economic perspectives, and higher densities are very common elsewhere throughout the world; however, we do not include higher densities in our scenarios largely because the densities of existing US metropolitan areas are currently so low compared to global cities, and because higher levels are not necessary to begin to dramatically reduce the resource intensities and other costs of our transportation system.

166 Newman and Kenworthy, "Gasoline Consumption and Cities."

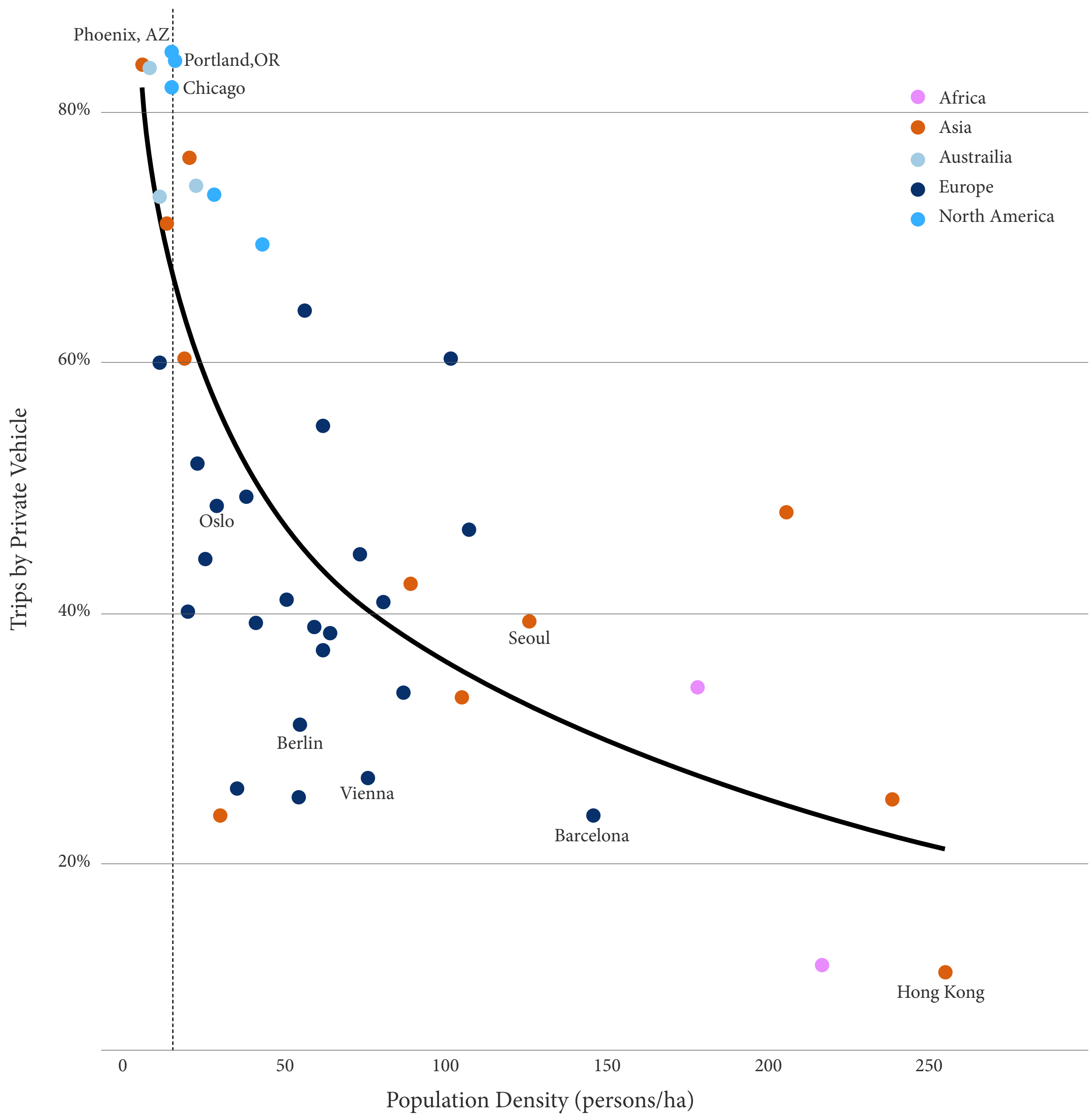

Figure 15. Population Density and Share of Trips by Private Car, UITP MCD

The figures show national and international data for density and mode share, drawing from the three datasets described above. Many cities are labeled on each plot in order to help illustrate what different densities and mode share look like in real cities.

Gray guidelines represent the 15 persons/ha thresholds that separate low- and medium-density classes in our scenario building. Figure 15 shows how US urbanized areas are far less dense than many global cities and have a far higher percentage of trips by cars. Denser cities have fewer trips by car. But density is not the only determinant of mode shares; many global cities, such as Helsinki and Oslo, have dramatically lower proportions of trips by car while having comparable densities to US cities included in the data.

Figure 16 uses Deloitte DCMI data to show the same relationship among a smaller selection of cities. Here, Amsterdam, Manchester, and Mexico City are similarly dense to many US cities with lower or dramatically lower car mode shares. Some cities, such as Oslo, have notably different positions in the two charts, reflecting the different time periods of the two datasets and potentially other differences in measurement. Nonetheless, the two plots show a consistent relationship.

Figure 17 uses ACS data to show the same relationship for all US urbanized areas with populations of more than half a million. The range of population densities is much smaller: no US urbanized areas have more than 30 persons/ha. The relationship between density and car use is still

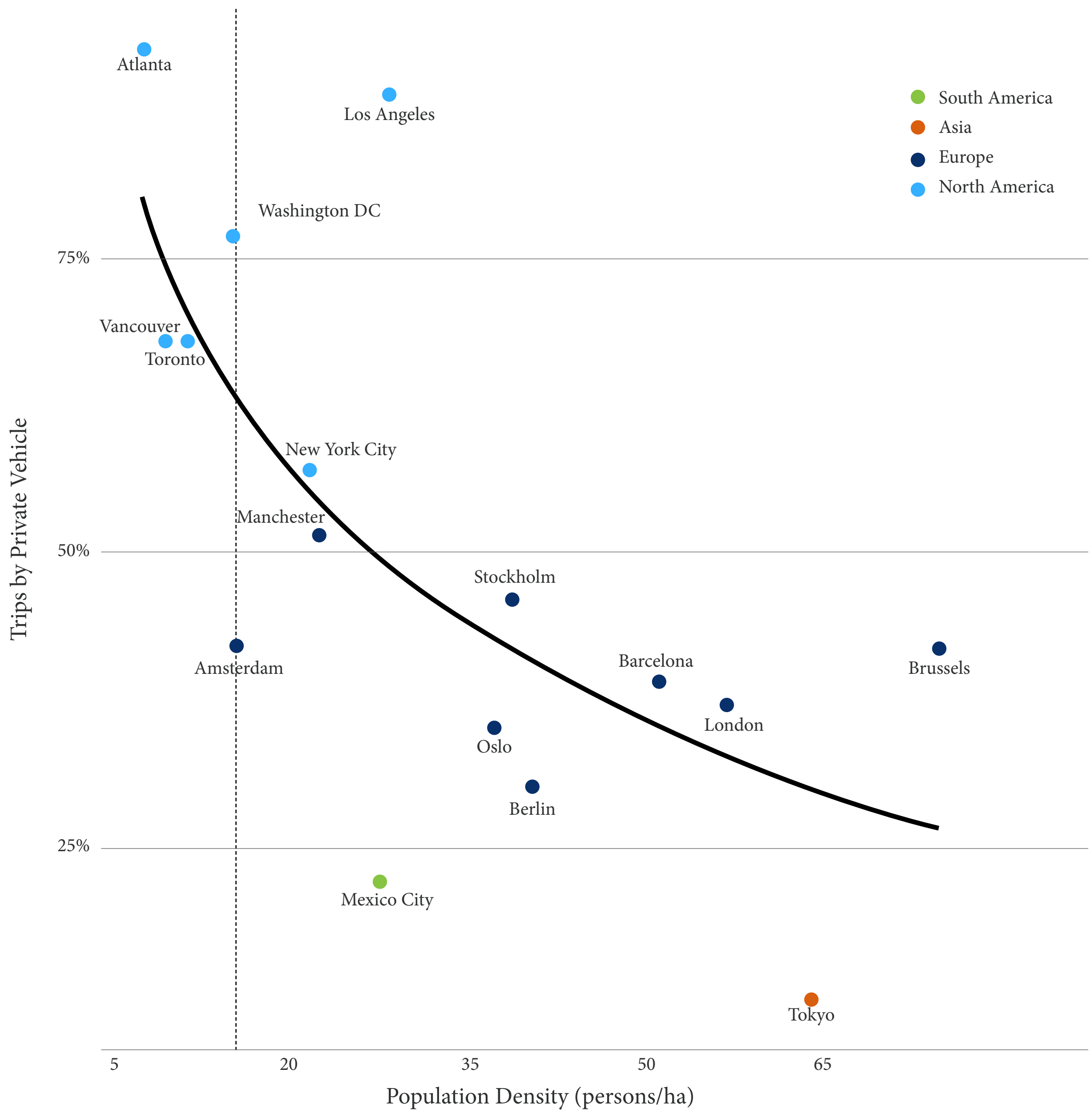

Figure 16. Population Density and Share of Trips by Private Car, DCMI data

present but less steep. Even relatively car-light urbanized areas in the United States, like New York–Newark, have expansive suburbs that lower their densities and increase their overall car dependence.

The plots in Figure 17 show how density is one essential feature that correlates consistently with mode share. However, the relationships between mode share and population density can be complex.[167] Our data show that cities with similar population densities may still have wildly different modal splits. Birmingham, England, has about 65 percent of trips occurring with private vehicles; Berlin has less than half of that. Both cities have similar population densities of around 50 persons/ha in the UITP MCD data.

To further provide a picture of existing US cities and the urbanized area spatial definition we use, we provide population density maps of the Chicago, NYC, and Los Angeles urbanized areas, followed by a histogram that shows the existing distribution of the US population by census

167 Teoh, Anciaes, and Jones, "Urban Mobility Transitions through GDP Growth"; Ewing and Cervero, ""Does Compact Development Make People Drive Less?"; Ewing et al., "Testing Newman and Kenworthy's Theory of Density and Automobile Dependence"; Kuss and Nicholas, "A Dozen Effective Interventions to Reduce Car Use in European Cities"; Kenworthy, "Urban Transport and Eco-Urbanism."

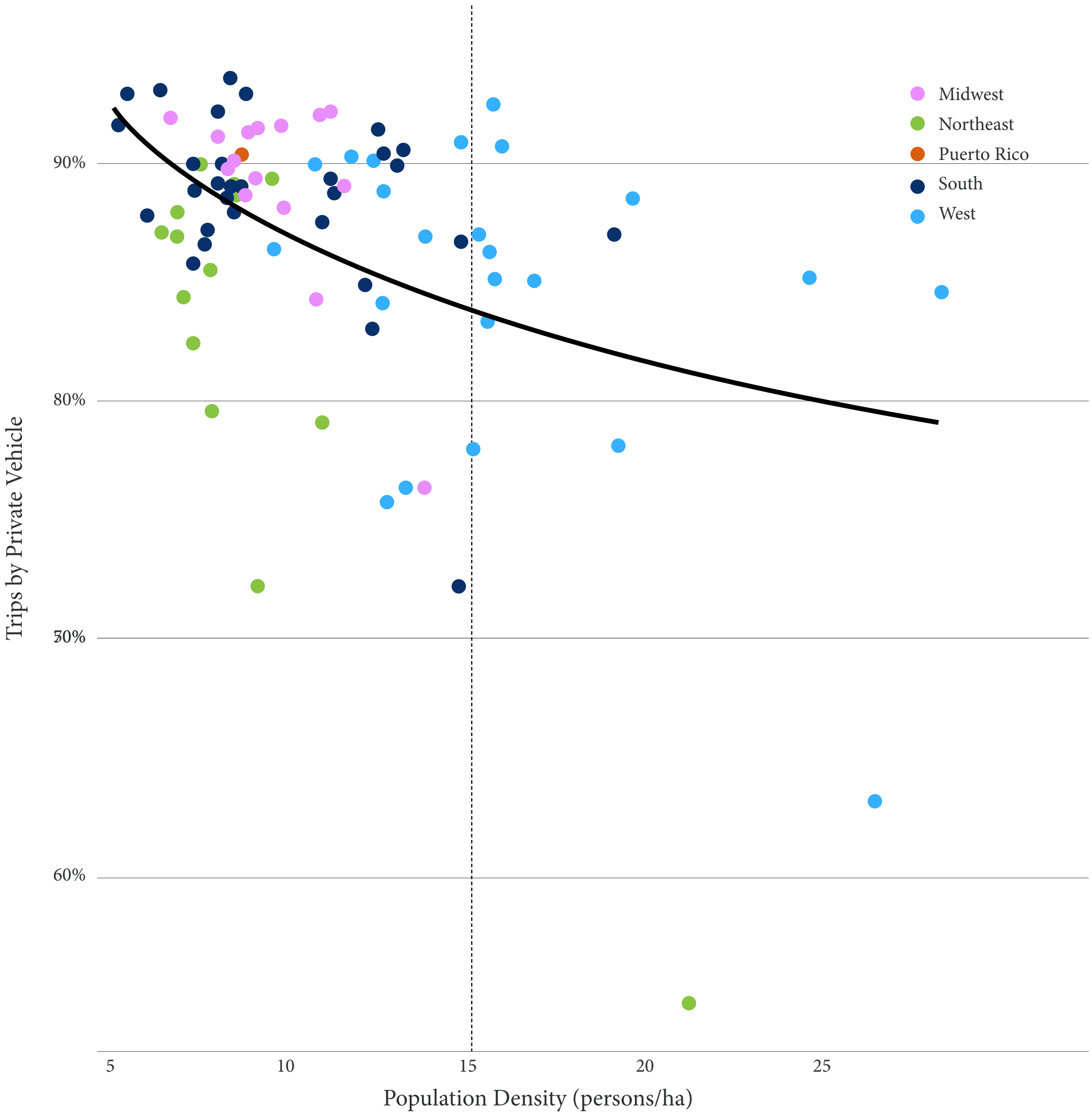

Figure 17. Population density and share of trips by private car, US cities

region. These three areas were chosen simply because they are all large cities that nonetheless have strongly varying urban forms. The maps will show how expansive sprawl and low-density outlying areas make each urbanized area far less dense than what one might expect for some of these cities, and the histogram will show the high proportion of the US population currently living in very-low-density urban areas, with fewer than 15 persons/ha.

Both New York City–Newark and Chicago urbanized areas have large central areas dramatically denser than our highest cut-off threshold of 15 persons/ha. However, the entire urbanized areas for both cities include expansive low-density suburban sprawl as well as spatially expansive car infrastructures, such as highways and parking lots. As a result of these factors, each urbanized area as a whole has far lower density than its city center or even its denser suburbs. The overall population densities for the two areas are about 22 persons/ha in NYC and 13 persons/ha in Chicago. Finally, the size and low density of much of Long Island contributes to the New York–Newark area having a lower population density than that of Los Angeles, despite the notorious sprawl of the latter.

Figure 21 shows the distribution of the urbanized population in the United States by population density. Most of the urbanized population lives in urbanized areas with between 5 and 15 persons/ha. Based on 2019 population estimates, 19 percent of the US population of about 330 million lives in rural areas. The other 81

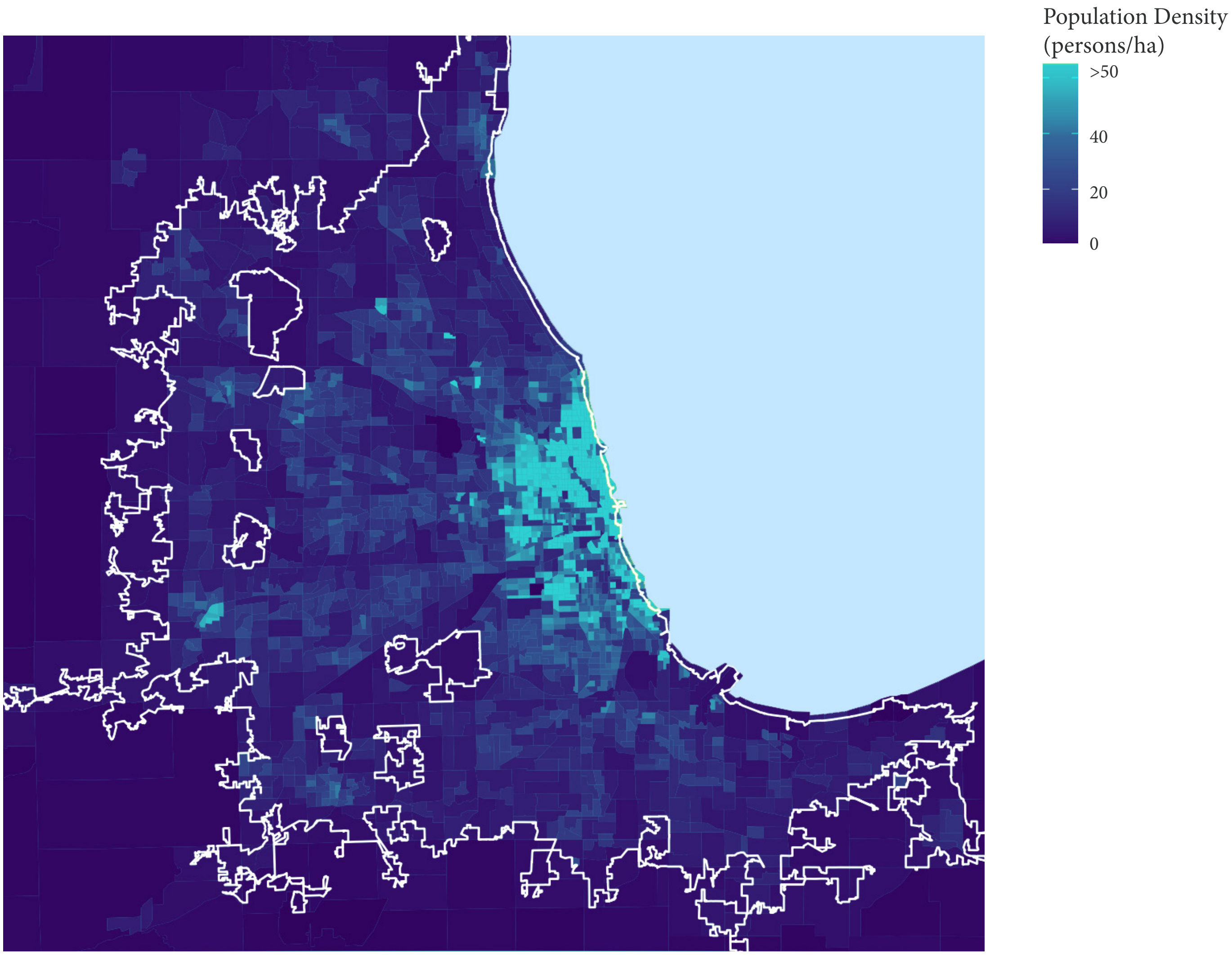

Figure 18. Chicago Urbanized Area Population Density

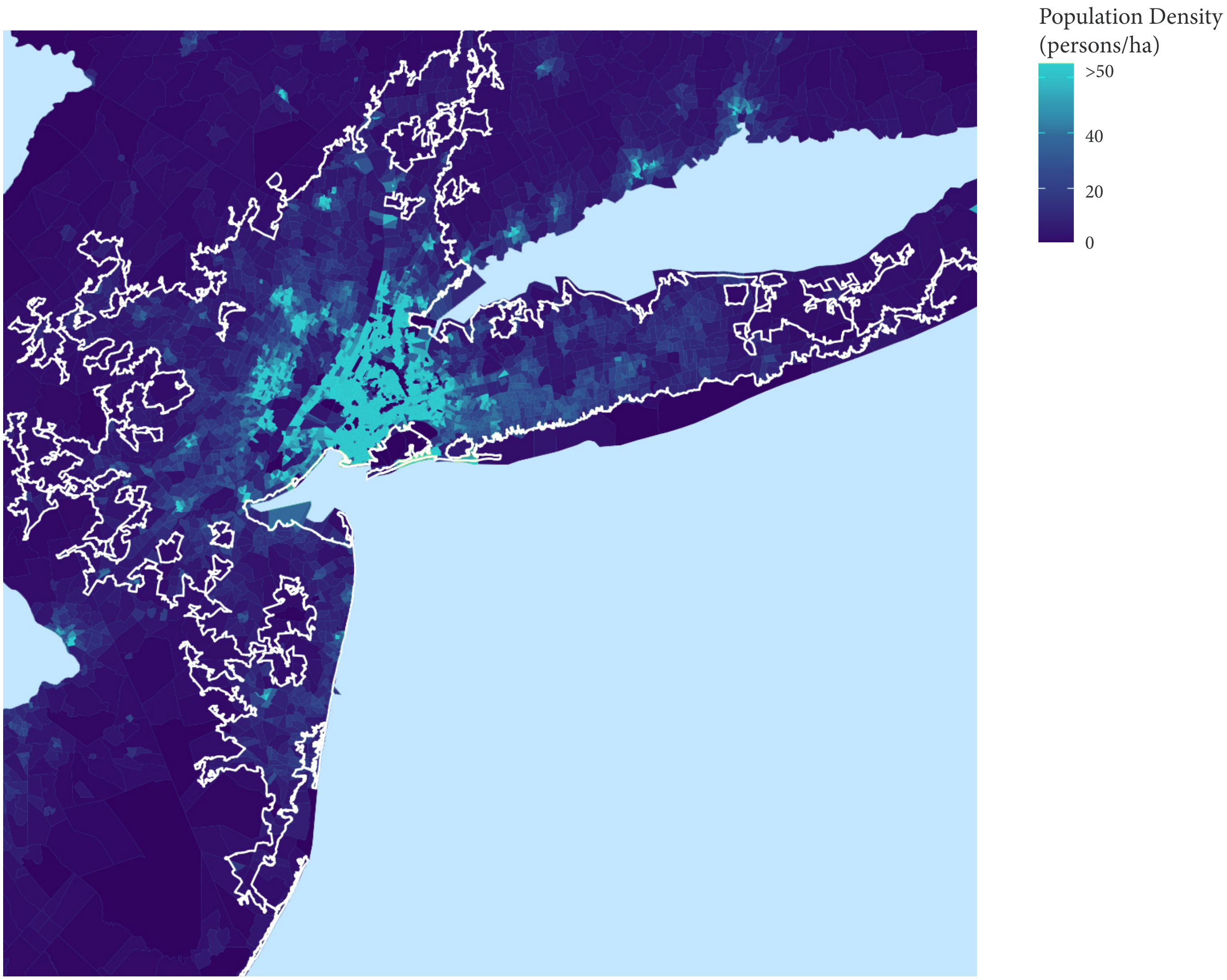

Figure 19. New York City–Newark Urbanized Area Population Density

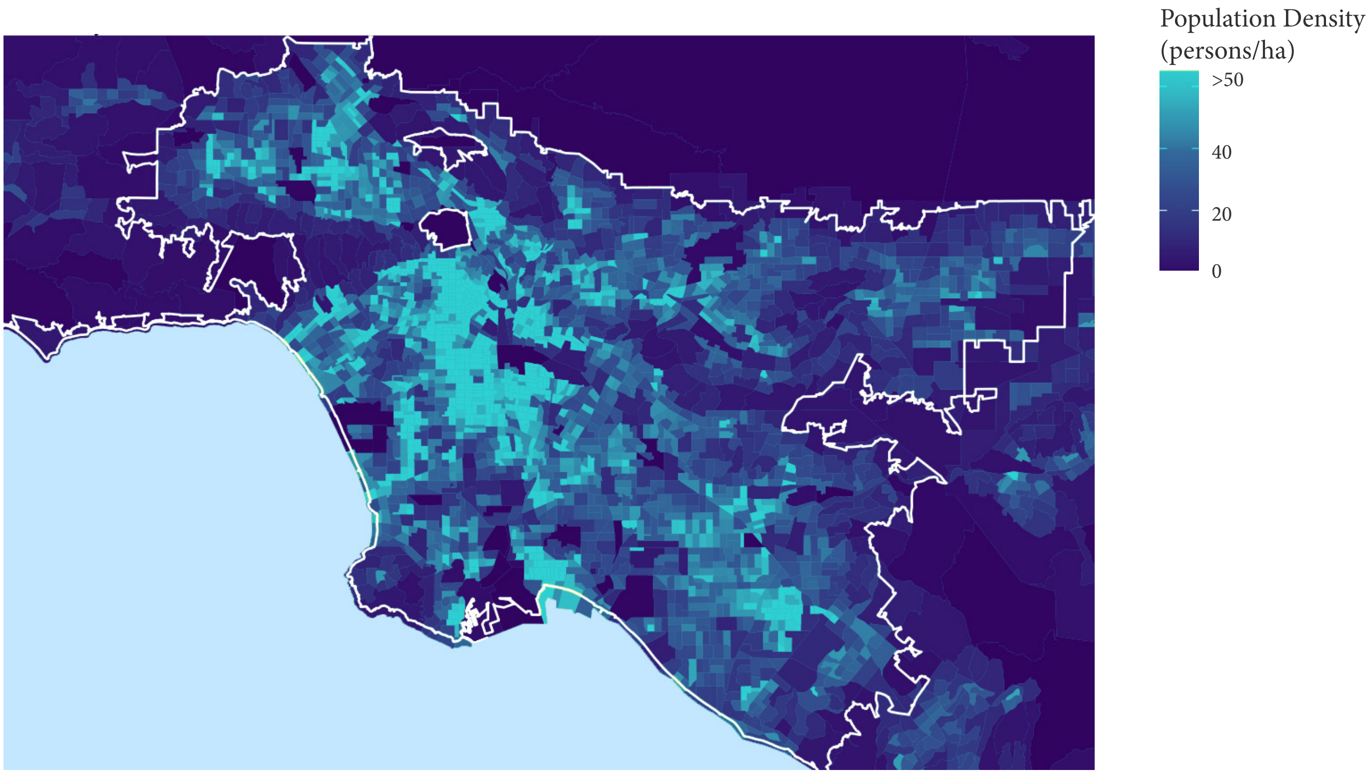

Figure 20. Los Angeles Area Population Density

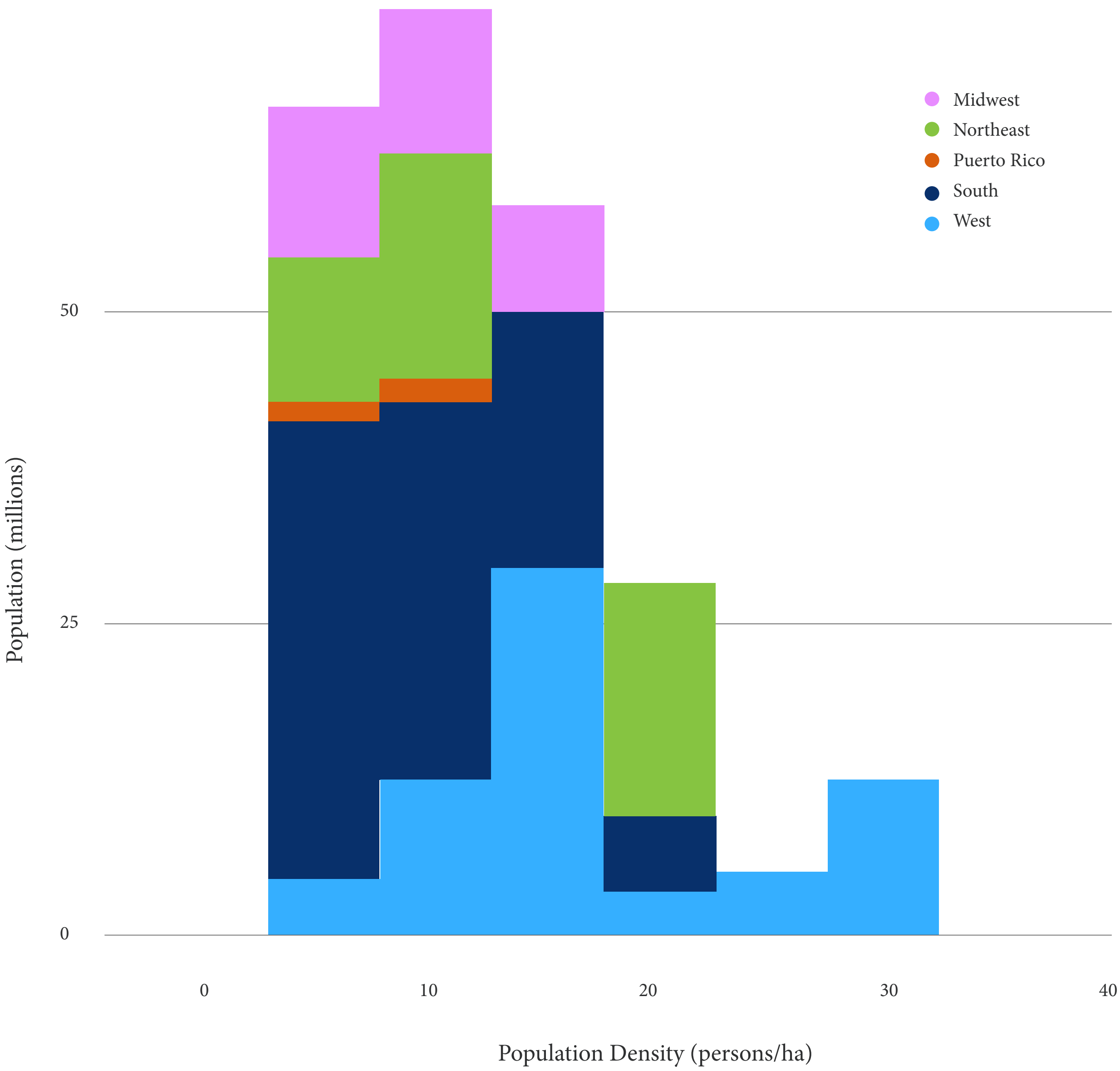

Figure 21. US Urbanized Population by Population Density and Region, ACS 2019 5-year estimates

percent are included in this histogram. This figure provides additional context on existing population densities in US urbanized areas.

Parameters for Density Classes

The flowchart that began this appendix showed that the mobility scenarios began with the allocation of population to the three density classes: rural, low-density urban, and medium-density. The discussion above provides justification for how these categories were defined and demonstrates why the population distribution across densities impacts mode share, and therefore likely vehicle and lithium requirements of a decarbonized transportation system.

The population distribution across density classes for the four scenarios was shown in the overview Table 5. These density classes parameters are also shown graphically in Figure 22.

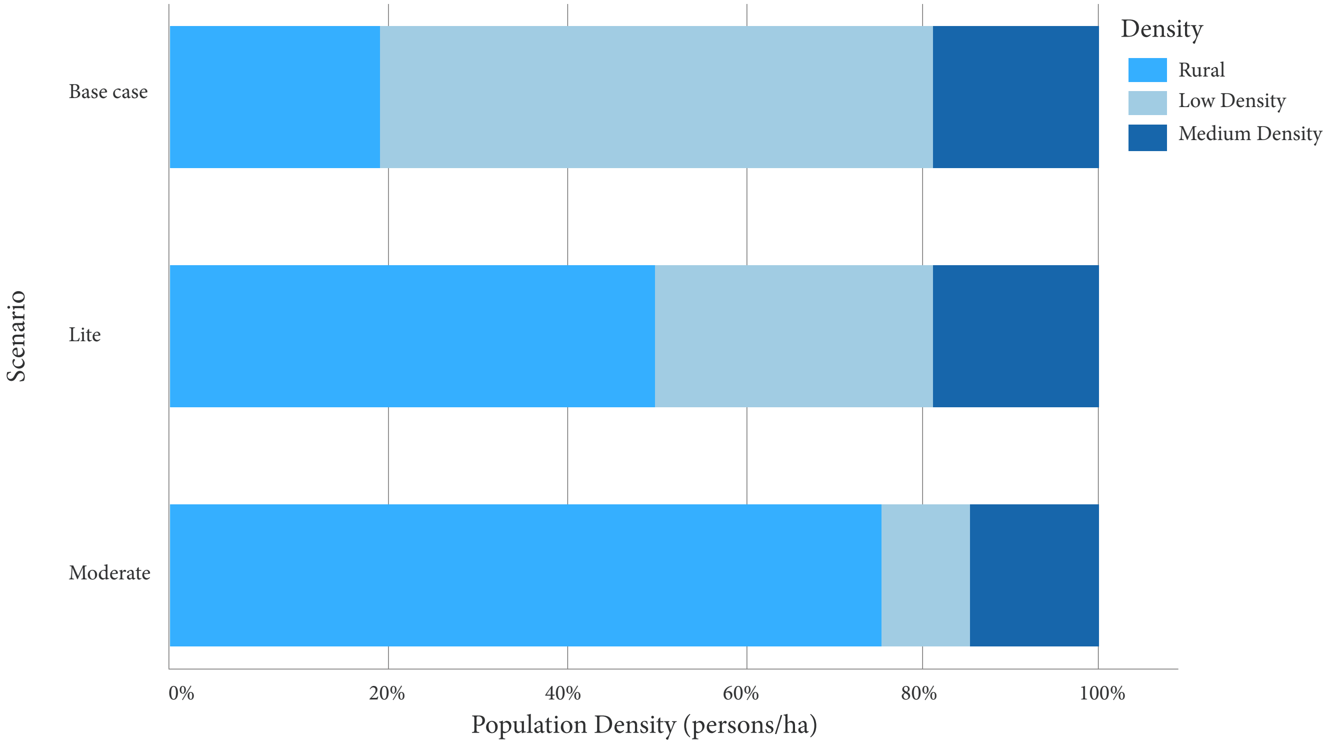

Figure 22. Densification scenarios

Global Mode Shares

The international datasets allow us to move from density classes to mode share to help inform the mode share parameters for our model. Figures 23 and 24 look beyond the relationship between density and car shares to the breakdown of travel modes across private cars, public transit, and active transit (walking and biking).

Figure 23 aggregates UITP cities by continents to show average mode share by density class for Asia, Australia, Europe, and North America, the continents for which UITP had the most data available. The plot shows both how public and active transit scale with density, but also that mixed modes are achievable at relatively low densities. Cities in Europe and Asia have a far lower percentage of travel happening by private cars, even at similar population densities. Figure 23 also shows that there are no urban areas with more than 50 persons/ha in North America or Australia in the UITP dataset.

Figure 24 shows the same city-level mode share breakdown from the Deloitte data. Car share reduces with density more straightforwardly. Public and active transit mode shares dwarf car shares in many global cities.

Figure 25 shows the same information for all US urban areas with over one million residents. It uses ACS data to show commute shares for all US urbanized areas with more than 1 million residents. In contrast to earlier figures that provided a global picture, all areas in the United States have a majority of their trips happening by car. The relationship between modal split and density is also much less apparent—indicating how other policies are also determinative of travel mode and also that every US urbanized area includes expansive, very-low-density sprawl.

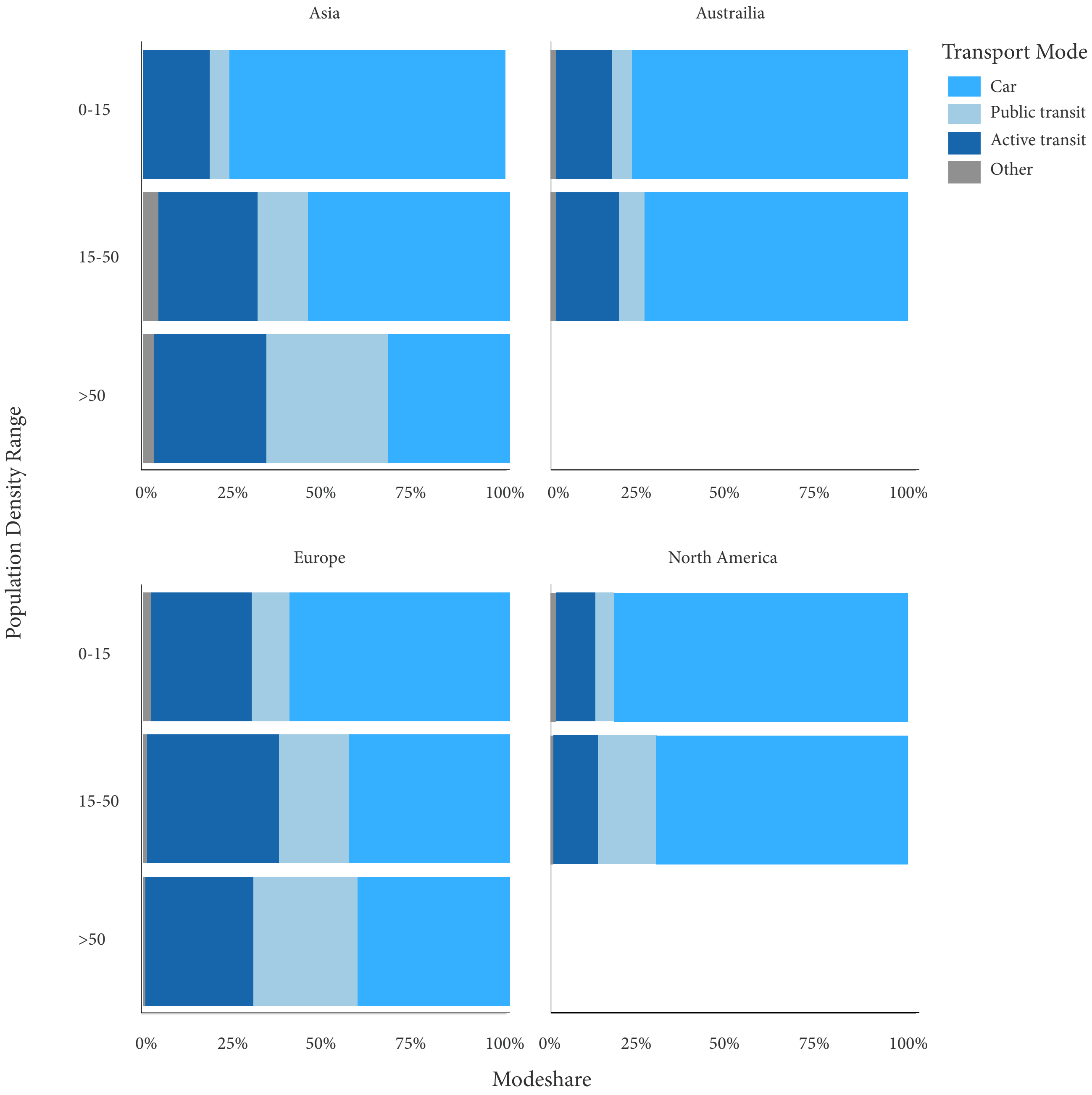

Figure 23. Mode shares by density and continent, UITP MCD

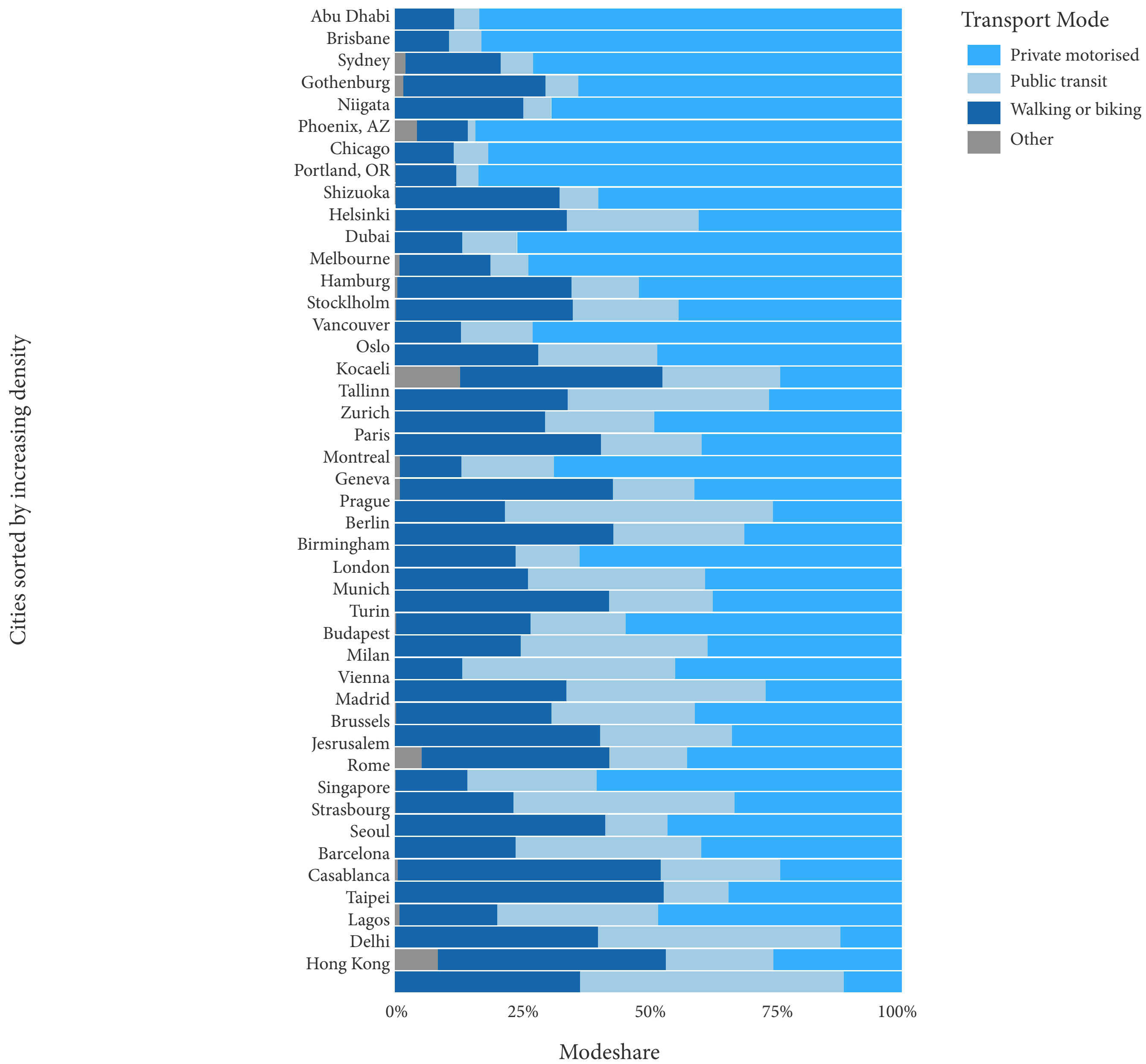

Figure 24. Mode shares across selected urban areas, DCMI data

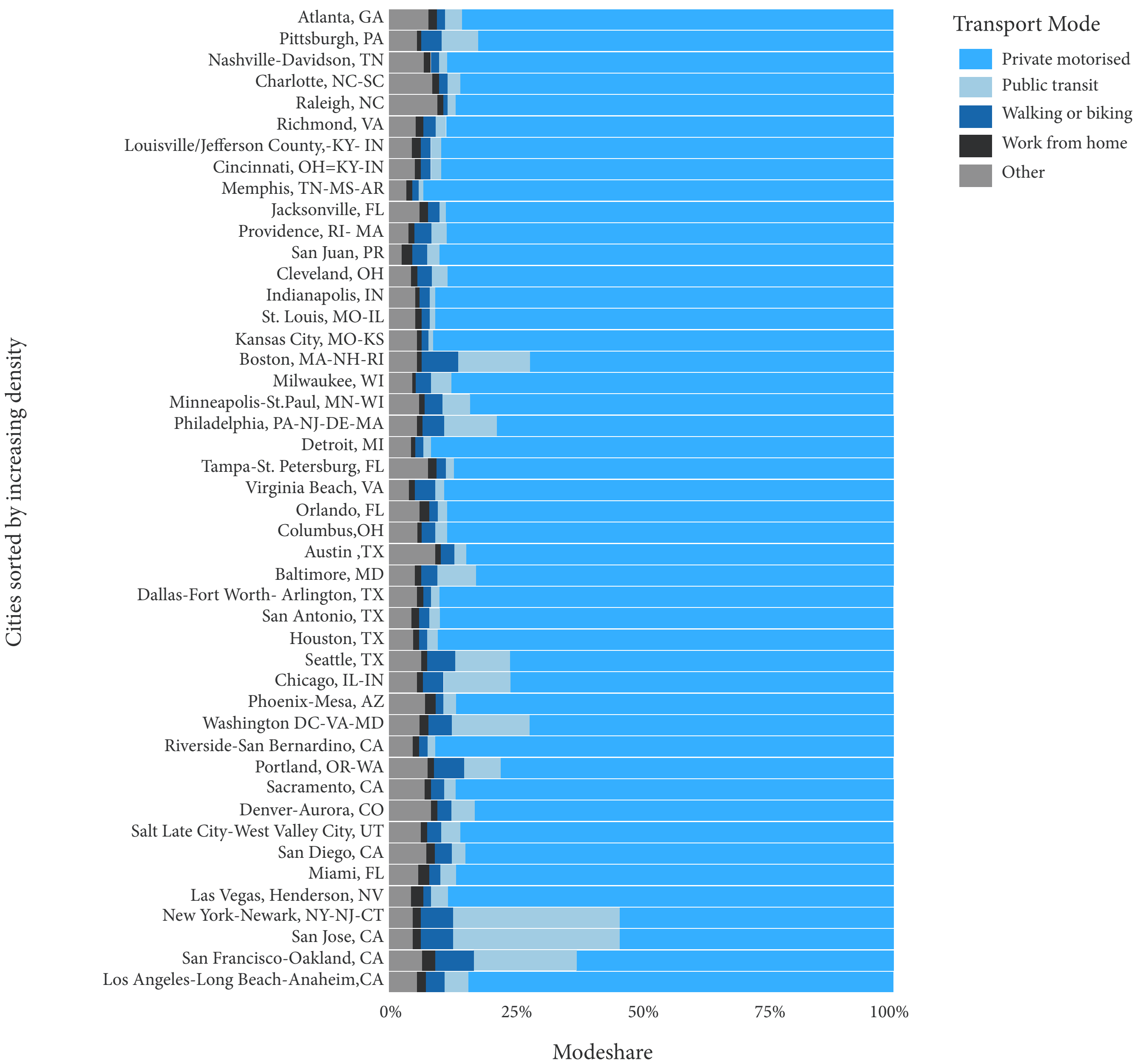

Figure 25. Commute shares across US Urbanized Areas with >1M residents

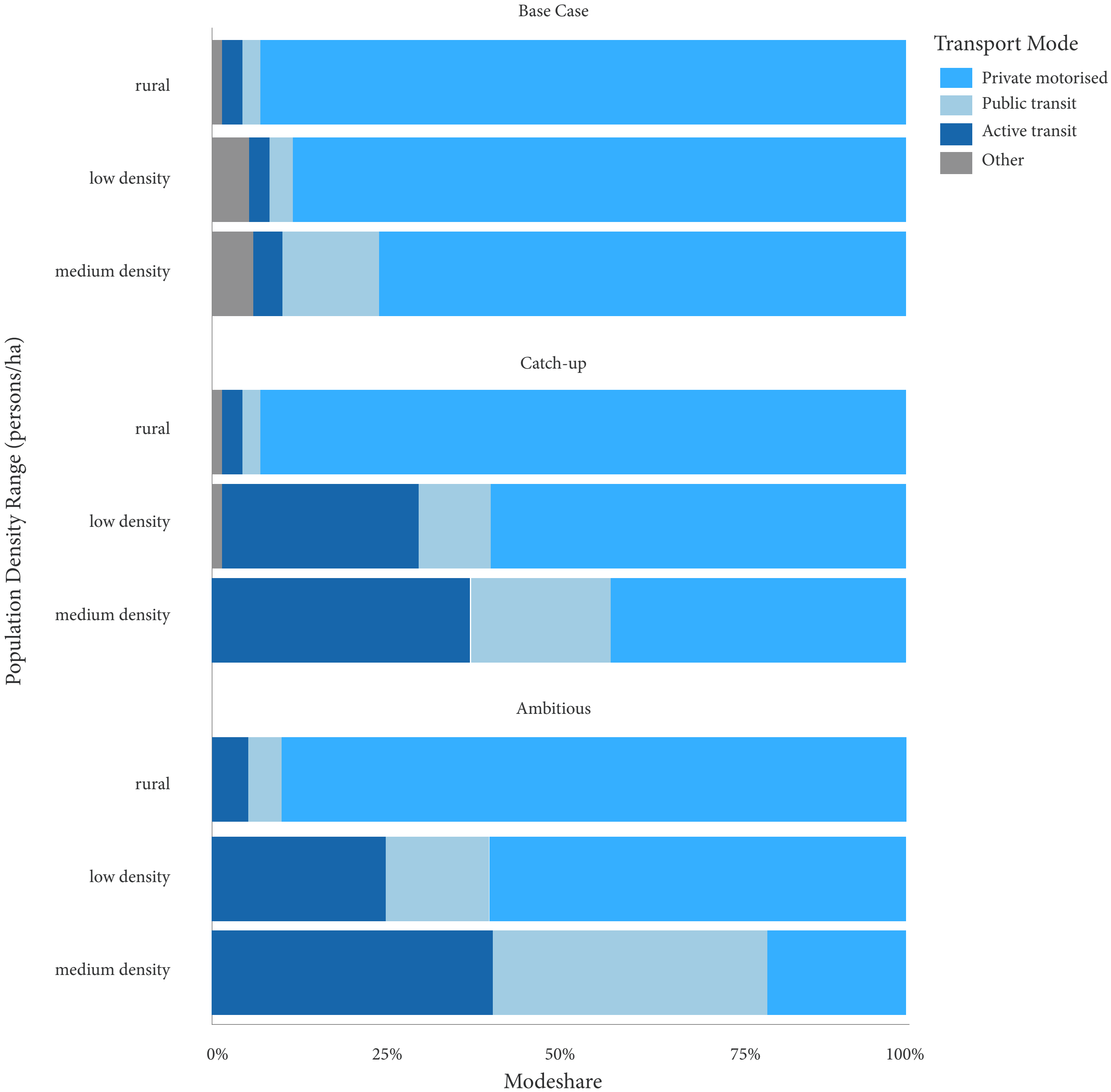

Figure 26. Mode share scenarios

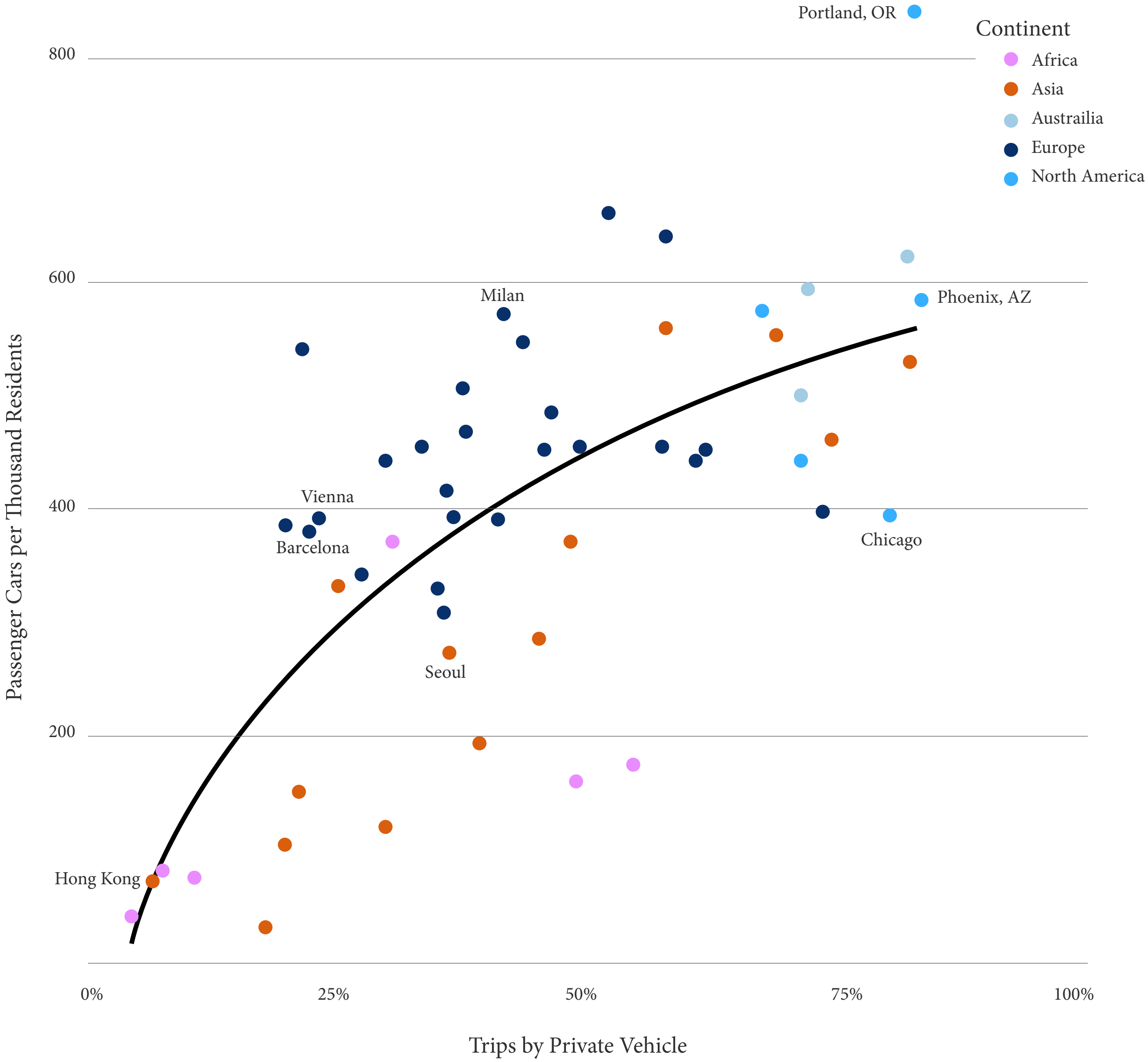

Figure 27. Car ownership as function of mode share

Parameters for Mode Shares

The model for vehicle requirements moved from population by density class to mode share by density class. The discussion above provides insight into reasonable target mode shares for different decarbonized mobility scenarios and shows what already exists across global cities.

As with the density class parameters, the mode share parameters for the four scenarios was shown in the overview Table 5 “Vehicle Requirements and Parameters across the Four Decarbonized Mobility Scenarios” that began this appendix. Mode share parameters are also shown graphically.

The mode share parameters used in Scenario 1 maintain current travel pattern by density in the United States; the parameters used in Scenarios 2 and 3 reflect the average mode split by density in European urban areas in the UITP MCD dataset. European areas were used because of their relatively thorough representation in the UITP data as well as their relative similarity to many US cities in terms of income and existing density. The mode share parameters in Scenario 4 reflect goals set by cities such as Vienna that are aiming to limit car use in favor of more sustainable and efficient modes of transportation. Figure 26 shows the mode share parameters across scenarios graphically; only percentages greater than 5 percent are labeled on this figure.

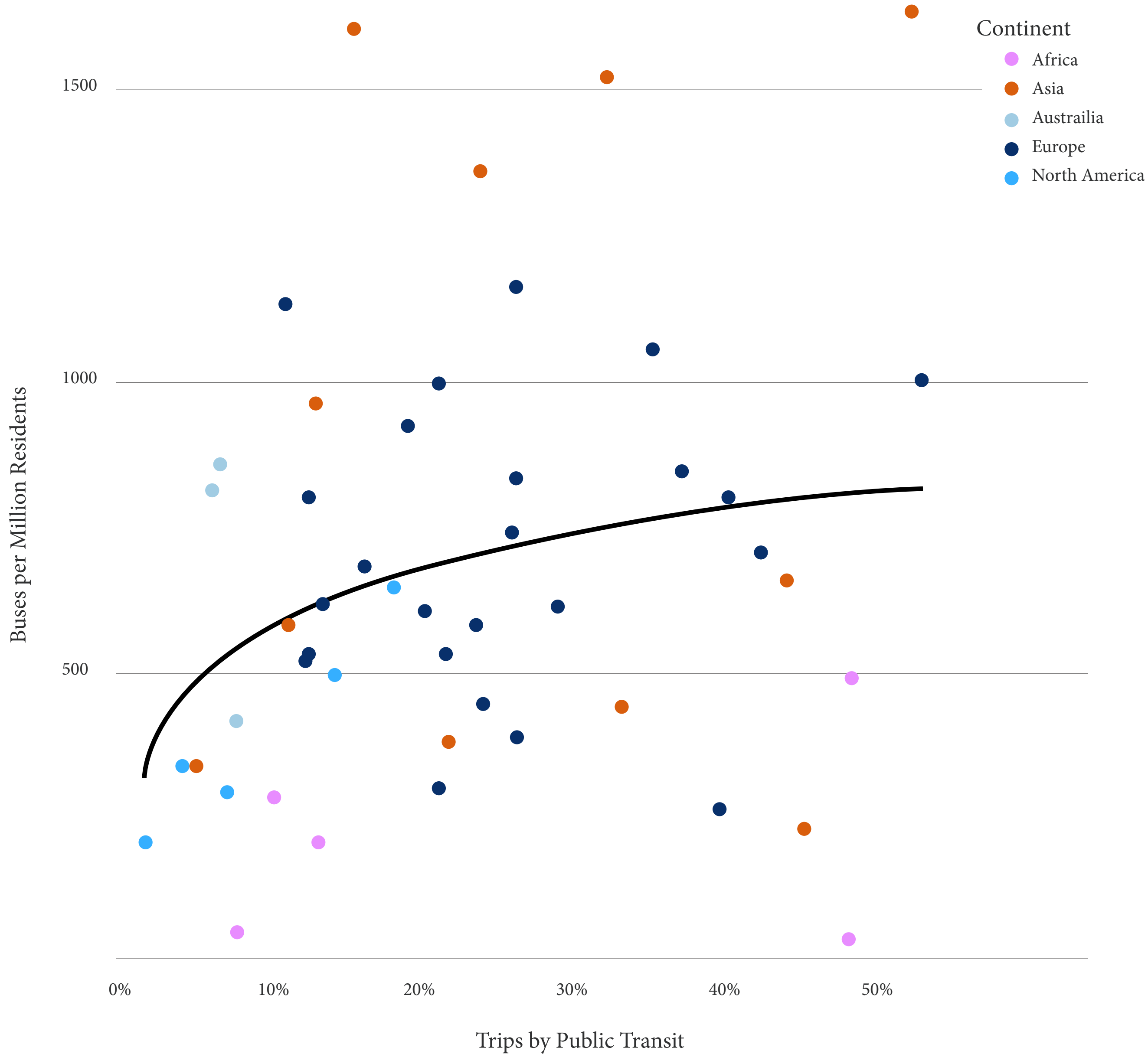

Figure 28. Bus fleet size per capita as function of mode share

Vehicle Requirement Rates

The last component used to define mobility scenarios is the rate at which travel by mode translates to vehicle needs. This rate is required to move from the estimated population traveling by different modes of transportation to vehicle requirements estimates. Vehicle requirement estimates can then be used to forecast lithium requirements for the mobility decarbonization pathways.

Data to inform how vehicle requirements relate to mode share and population is only available from UITP data. However, the current number of cars, public transit buses, and school buses in the United States is available from the Department of Energy (DOE) and World Resources Institute (WRI). We used the existing vehicle counts by mode to benchmark the vehicle requirements rates for our base case scenario. For Scenarios 3 and 4, the wide divergence in the vehicle requirement rates by mode in the UITP data is used to estimate reasonable but more ambitious vehicle requirement rates.

Figures 27 and 28 show how car ownership and the number of transit buses per capita relate to the share of travel happening by private car or mass transit, respectively.

As with the other relationships, there is a large degree of variation despite an underlying correlation between car mode share and cars per thousand residents. Portland, Oregon, shows extremely high levels of car ownership—even higher than Phoenix, Arizona—despite having a slightly smaller share of trips by car. The different vehicle requirements parameters reflect how levels of car use can translate differently to total numbers of cars.

The relationship between bus requirements and public transit mode share shows an even wider degree of variation while also maintaining a rough, positive correlation. Lower bus requirements per capita given similar shares of trips by public transit will tend to have a public transit system that makes heavier use of streetcars, light and heavy passenger rail, and other public transit vehicles. This will be relevant for our resource intensity analysis because these vehicles will tend to demand smaller amounts of lithium relative to e-buses.

Parameters for Vehicle Requirements

In the model flowchart that began this section, vehicle requirement rates were the last set of parameters required to estimate vehicle requirements. Vehicle requirement rates allow us to move from the numbers of people traveling predominately by a particular mode to vehicle requirements in terms of cars and buses. The car requirement rate in rural areas does not change across any scenario or set of parameters; the base case vehicle requirement rate is used for cars in rural areas across every scenario (Table 5).

Vehicle requirement rates refer to the number of cars or buses needed to transport a given population traveling primarily by car or public transit. One way to think about these rates is as roughly the ratio of car ownership to car trips (or ratio of buses in operation to public transit trips). Scenarios with lower car requirement rates will have more car share systems and carpooling, shifting norms around private car ownership, and fewer multi-car households. Lower bus requirement rates reflect more streetcars, light rail, and other public transit vehicles that demand smaller amounts of lithium relative to e-buses. In Scenario 4, school buses requirements were decreased somewhat to reflect the likelihood that denser living and less car traffic would allow school buses to operate more efficiently. Vehicle requirement rates, particularly for Scenario 1, were benchmarked to current levels in the United States, which were determined from WRI and DOE data and existing population and mode share data in the United States. Vehicle requirement rates for other scenarios were determined by visual and statistical analysis of UITP MCD data.

Decarbonized Transportation Outcomes: Vehicle Requirements Across Four Scenarios

After defining our scenarios, we can estimate the total vehicle requirements for different decarbonized mobility scenarios. These model results were already shown in Table 5, but are shown again graphically in Figures 29 and 30.

What Is Car Dependency?

We define car dependency as the set of policies that enforce mass private car ownership by making it difficult, slow, unsafe, unhealthy, and/or illegal to reach many necessary destinations without owning a car. These policies may include the following:

- **Investment in car infrastructure over infrastructure for public transit.** When it was constructed, the interstate highway system in the United States was the largest investment in public infrastructure in history.[168] Highways still tend to get four times as much federal funding as public transportation.[169] Car dependency is something that is built, and the physical infrastructure of car dependency entails many of the largest and most sustained public investments in US history.
- **Car-oriented development laws.** These include parking minimums, minimum lot sizes, free or underpriced on-street parking, mandated traffic impact analyses for new housing construction, and other laws that mandate car-oriented development that make other modes of transport less safe, practical, and pleasant. Parking minimums make housing and other forms of development more expensive, entailing huge financial and spatial subsidies for personal car ownership. Zoning and land-use codes mandate lower-density development that can encourage car use while hobbling most forms of public transit in nearly all of the United States, including major cities.[170]
- **Allocation of land area and public space for cars.** Most public space in US cities is exclusively or practically only for cars. Streets make up 80 percent of all public space in US cities;[171] most space on streets

168 Clayton Nall, The Road to Inequality: How the Federal Highway Program Polarized America and Undermined Cities (Cambridge and New York: Cambridge University Press, 2018).

169 Jeff Davis, "Explainer: What the '80-20 Highway-Transit Split' Really Is, and What It Isn't," Eno Center for Transportation, July 26, 2021, https://www.enotrans.org/article/explainer-what-the-80-20-highway-transit-split-really-is-and-what-it-isnt/.

170 Emily Badger and Quoctrung Bui, "Cities Start to Question an American Ideal: A House with a Yard on Every Lot," New York Times, June 18, 2019, sec. The Upshot, https://www.nytimes.com/interactive/2019/06/18/upshot/cities-across-america-question-single-family-zoning.html.

171 National Association of City Transportation Officials, "Streets," July 11, 2013, https://nacto.org/publication/urban-street-design-guide/streets/.

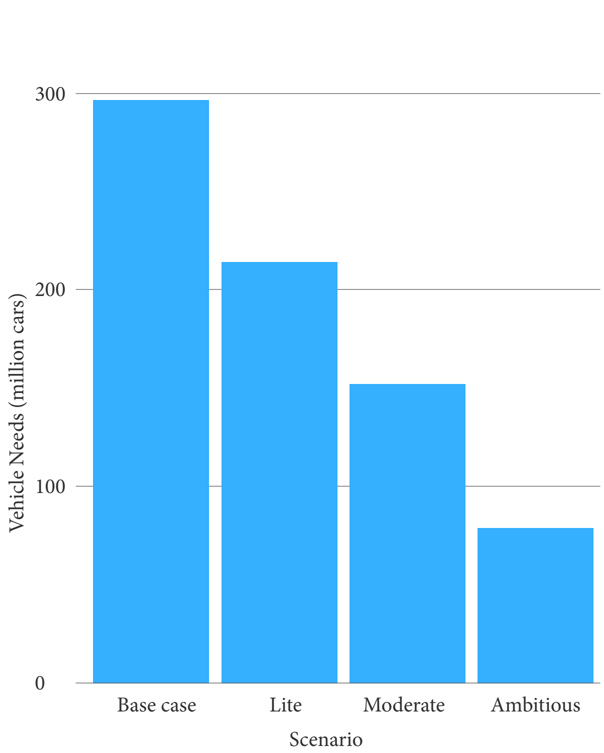

Figure 29. Estimated car needs by decarbonized transportation scenario

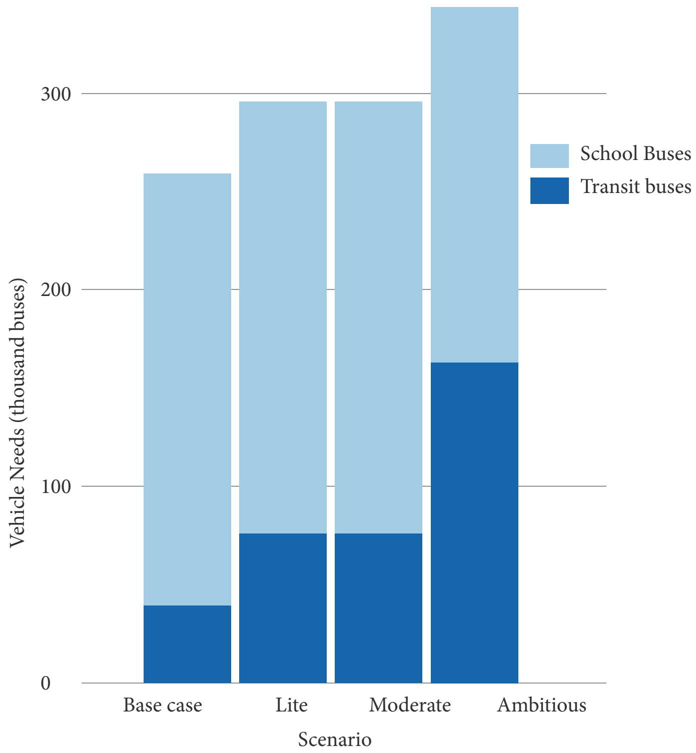

Figure 30. Estimated bus needs by decarbonized transportation scenario

is allocated for cars in the form of travel or parking lanes. According to civil engineer Samuel Schwartz, cars are given 30 to 40 percent of total space in US cities.[172] The immense allocation of public space to cars is an essential feature of car dependency.

- **Under-regulation of air, noise, greenhouse gas pollution, and vehicle safety.** Car use poses massive economic externalities. Traffic violence is a leading cause of death for US residents until the age of 45, and it is the leading cause of years of potential life lost. Noise pollution has a surprising array of negative social consequences, causing increased levels of violent crime and a startlingly high proportion of neurodegenerative conditions.[173] Vehicle safety in the United States is not regulated from the perspective of persons outside of the vehicle, allowing automakers to continue contributing to the high and rising level of vehicular fatalities in the United States without consequence to themselves.[174] These factors, combined with the massive proportion of land area given to cars, make large swaths of the United States dangerous and unhealthy for people outside of them.
- **Financial subsidies for cars and oil.** Cars are heavily subsidized in the United States. The gas tax far from covers the costs of roads in every US state.[175] Automakers have been beneficiaries of large public bailouts, as during the 2008 financial crisis.[176] Electric cars are extremely heavily subsidized, while many other, more sustainable modes of transportation—such as bikes and e-bikes—typically are not.
- **Foreign policy conducted to ensure a low and steady price of gasoline.** US foreign policy has often been conducted in ways that have protected oil supply and relatively stable oil prices.[177]

172 Quoted in Johnny Diaz, "Cities Close Streets to Cars, Opening Space for Social Distancing," New York Times, April 11, 2020, sec. U.S., https://www.nytimes.com/2020/04/11/us/coronavirus-street-closures.html.

173 Timo Hener, "Noise Pollution and Violent Crime," Journal of Public Economics 215 (November 1, 2022): 104748, https://doi.org/10.1016/j.jpubeco.2022.104748; "Traffic Noise May Raise Risk of Alzheimer's, Other Dementias," Medical News Today, September 13, 2021, https://www.medicalnewstoday.com/articles/dementia-traffic-noise-may-raise-risk.

174 Kea Wilson, "Vehicle Safety Assessments Don't Protect Pedestrians," Streetsblog USA, April 29, 2020, https://usa.streetsblog.org/2020/04/28/vehicle-safety-standards-dont-protect-pedestrians/.

175 Janelle Fritts, "How Are Your State's Roads Funded?," Tax Foundation (blog), September 11, 2019, https://taxfoundation.org/states-road-funding-2019/.

176 "What Did America Buy with the Auto Bailout, and Was It Worth It?," Marketplace (blog), November 14, 2018, https://www.marketplace.org/2018/11/13/what-did-america-buy-auto-bailout-and-was-it-worth-it/.

177 Gregory Brew, "How Private Oil Companies Took Over U.S. Energy Security," May 2022, https://foreignpolicy.com/2022/05/16/us-oil-companies-history-energy-security-gas-fossil-fuels-war-climate-europe/.

The result of these and similar policies is a built environment throughout nearly the entire developed area of the United States that is hostile, dangerous, and/or impractical to navigate outside of a car. We are now entrenched in car dependency; vast amounts of spending by all levels of government have built it. Many institutions and aspects of our culture or daily routines have developed around it. However, we stand to gain enormously by shifting course. Countries and cities around the world have been demonstrating how quickly it can be done and how popular it can be to do so.[178]

Lithium-Ion Battery Technology

How do batteries degrade and die?

The SOH of LIBs is difficult to predict because it is a factor of other parameters and cannot be measured directly. These factors are user dependent, like charging and e/discharging habits; environment dependent, like temperature; or battery dependent, like capacity.[179] A lower depth of discharge allows batteries to last longer. Keeping the state of charge—the amount of power available in the battery—high without reaching the maximum battery capacity also allows the battery to last longer. This indicates that an environment that allows for short driving distances and abundant charging infrastructure is ideal for battery SOH. Because depth of discharge is a function of capacity, capacity also influences the SOH. Theoretically, larger batteries will have a longer lifetime if they undergo the same charging and discharging cycles of a smaller battery. Temperature influences the performance of an LIB. The optimal temperature range for an LIB is 15–35 °C.[180] Temperatures below this range decrease performance by causing loss of conductivity and increase in internal resistance. Higher temperatures accelerate aging and increase the risk of thermal runaway.

Determining SOH accurately is important for battery safety management. Direct measurement methods are precise, but they are difficult to obtain because of the need for special equipment and experiment conditions. Therefore, most methods to determine SOH are through indirect measurements called health indicators (HI). HIs are historical charging data that are mathematically manipulated to reflect the internal electrochemical reaction indicating the level of battery degradation.[181] Commonly used HIs to determine SOH are internal resistance, temperature, voltage drop, and constant current charging time. Using internal resistance as the health factor to determine SOH gives accurate early-stage predictions.[182] There is a strong linear relationship between constant current charging time and SOH, and constant current charging time is used as a health factor to determine SOH.[183] Voltage drop is also used as a health factor in model-based estimations of SOH.[184] Differential voltage analysis and incremental capacity analysis are two additional methods to estimate highly accurate SOH values using transformed data.[185]

178 Kersley, “People Hate the Idea of Car-Free Cities—Until They Live in One”; Vock, “How Anne Hidalgo’s Anti-Car Policies Won Her Re-Election in Paris”; Romeo, “How Oslo Learned to Fight Climate Change.”

179 Ning He, Cheng Qian, Chao Shen, and Yigeng Huangfu. “A Fusion Framework for Lithium-Ion Batteries State of Health Estimation Using Compressed Sensing and Entropy Weight Method,” ISA Transactions, 2022, https://doi.org/10.1016/j.isatra.2022.10.003.

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181 Y. Guo, K. Huang, X. Yu, Y. Wang, “State-of-health estimation for lithium-ion batteries based on historical dependency of charging data and ensemble SVR,” Electrochimica Acta, 428, (2022): 140940. https://doi.org/10.1016/j.electacta.2022.140940.

182 Mohammed Hussein Saleh Mohammed Haram, Jia Woon Lee, Gobbi Ramasamy, Eng Eng Ngu, Siva Priya Thiagarajah, and Yuen How Lee, "Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges," Alexandria Engineering Journal 60, no. 5 (2021): 4517-4536.

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185 Cuicui Liu, Xiankui Wen, Jingliang Zhong, Wei Liu, Jianhong Chen, Jiawei Zhang, Zhiqin Wang, and Qiangqiang Liao, “Characterization of Aging Mechanisms and State of Health for Second-Life 21700 Ternary Lithium-Ion Battery,” Journal of Energy Storage 55 (2022): 105511, https://doi.org/10.1016/j.est.2022.105511.

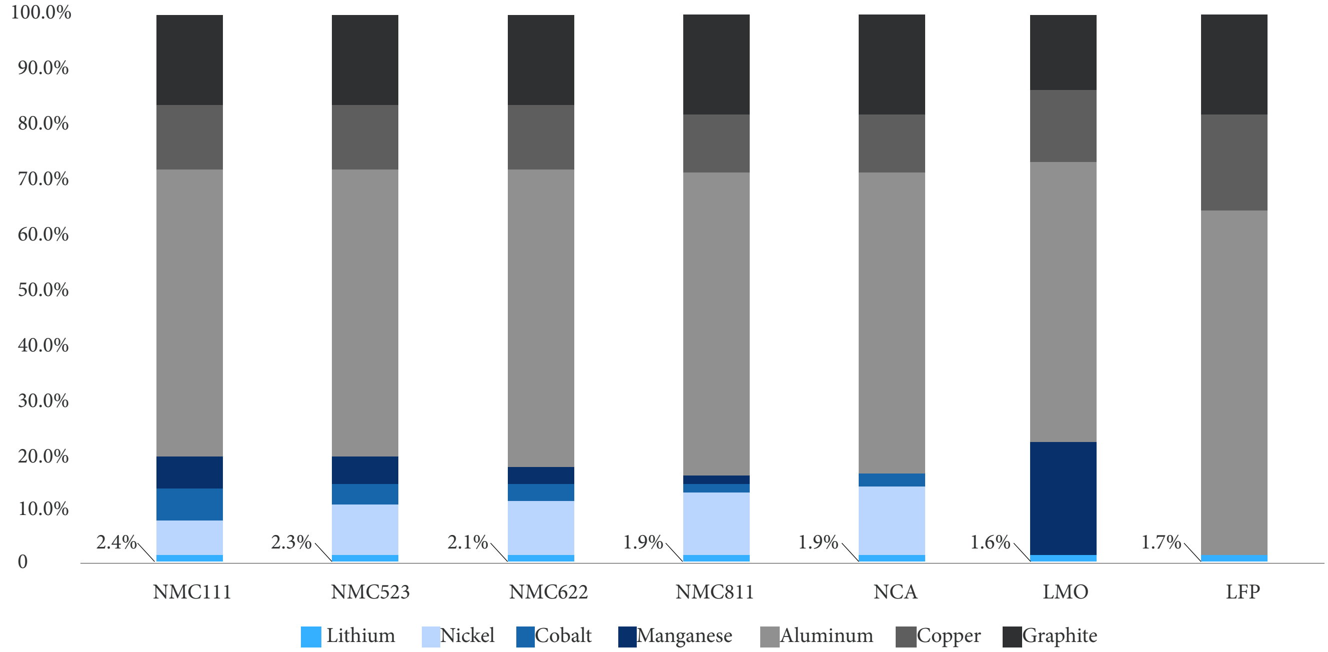

Figure 31. Relative Mineral Content in Various LIB Chemistries

EV Battery Warranties

LIBS are recommended to be replaced in EVs at 80 percent SOH. SOH is the EV's maximum battery charge divided by the rated capacity. No federal laws in the United States directly address battery degradation and warranty requirements. However, in August 2022, the California Air and Resources Board approved the Advanced Clean Cars II rule, making California the first state in the United States to implement a battery EV warranty period. The regulation requires batteries in EVs to maintain at least 75 percent of the rated capacity for 8 years or 100,000 miles for model year vehicles 2031 and later. Related to battery durability over time, this regulation also requires vehicles to maintain at least 80 percent of their electric range for 10 years or 150,000 miles.

To reach this goal, the California policy uses a phased approach that requires warranties to cover 70 percent of the rated capacity for 2026 through 2030 model year vehicles.[186] Despite the lack of legal incentive, most original equipment manufacturers today provide warranties that cover LIBs for 8 years or 100,000 miles.

186 "Advanced Clean Cars II." Advanced Clean Cars II. Accessed December 15, 2022. https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/advanced-clean-cars-ii

EV Sales and Retirements

Table 7: Regression for EV Stock

Projection Type	Mode	Transportation Future Scenario	R2	Polynomial order	Function
Stock	Transit Bus	Scenario 1	.9952	3	y = 3.369316878x3 - 20,480.5571975018x2 + 41,496,478.1118077x - 28,025,233,014.3114
Stock	Transit Bus	Scenario 2	.9998	3	y = 5.4101288958x3 - 32,810.7327561504x2 + 66,328,588.3947035000x - 44,695,252,504.5018
Stock	Transit Bus	Scenario 3	.9999	3	y = 5.8124665579x3 - 35,241.5827488313x2 + 71,224,163.7550019x - 47,981,705,541.4614
Stock	Transit Bus	Scenario 4	1.0000	3	y = 10.0643743579x3 - 60,930.7541054873x2+ 122,960,356.250431x - 82,712,677,956.6852
Stock	School Bus	Scenarios 1–3	.9996	3	y = 3.7126595054x3 - 22,357.9282183206x2 + 44,882,261.0975993x - 30,033,907,640.8713
Stock	School Bus	Scenario 4	.9993	2	y = 146.3886195201x2 - 587,306.339892098x + 589,259,788.282788
Stock	Passenger Cars	Scenario 1	1.000	3	y = 6,473.63363266364x3 - 39,116,912.0945412x2 + 78,787,920,640.3889x - 52,897,279,864,132.
Stock	Passenger Cars	Scenario 2	.9995	2	Y = 172,557.552939913x2 - 695,264,328.267829x + 700,333,763,867.394
Stock	Passenger Cars	Scenario 3	.9995	2	y = 122,167.917651265x2 - 492,205,420.17016x + 495,763,821,651.905
Stock	Passenger Cars	Scenario 4	.9997	2	y = 61,213.0640961815x2 - 246,571,056.371998x + 248,301,604,509.68

Vehicle retirement modeling

Vehicle retirement rates (i.e., vehicle failures) are estimated using a Weibull distribution assuming an average lifetime of 15 years and using a shape parameter of 7, a method that accords with similar modeling activities for EVs. The Weibull shape parameter was chosen because values over 1 indicate wear out failure.[187] The scale parameter is defined as the time it takes for 63.2 percent of the components analyzed to fail. The scale parameter was calculated using the following equation:

Eq (1): $\eta=t/e\text{^}(\Gamma(1+1/\beta))$,

where t is the average lifetime of a battery, β is the shape parameter, and η is the scale parameter. Using these parameters for the Weibull distribution gave the following probability of battery failure over time.

To translate the stock turnover model to new vehicle sales, the following equation was used:

Eq(2): New EV Sales = VSt(t) – VSt(t-1) + Vret(t),

where VSt is the vehicle stock in a given year t and VRet is the number of vehicles retired in a given year t. VRet is calculated based on the fleet turnover model and is thus a function of sales in previous years. The time series data of stock, sales, and retirements for passenger EVs are provided in Tables 9 and 10.

187 Arabali Amirsaman et al., "Optimum Sizing and Siting of Renewable-Energy-Based DG Units in Distribution Systems," Optimization in Renewable Energy Systems, 2017, 233–77, https://doi.org/10.1016/b978-0-08-101041-9.00007-7.

Table 8: Vehicle Probability of Failure over Time

Years since car sold	Probability of failure
0	0
1	0.006
2	0.013
3	0.019
4	0.029
5	0.045
6	0.062
7	0.086
8	0.114
9	0.146
10	0.182
11	0.222
12	0.263
13	0.320
14	0.392
15	0.466
16	0.536
17	0.600
18	0.657
19	0.707
20	0.750
21	0.786
22	0.817
23	0.843
24	0.866
25	0.885
26	0.901
27	**0.915**
28	**0.929**

Table 9: US EV passenger car stock, sales, and retirements for Scenarios 1 and 2

	Scenario 1			Scenario 2		
Year	EV Stock	EVs Sold	EVs Retired	EV Stock	EVs Sold	EVs Retired
2010	3774	3774	24	3774	3774	24
2011	13524	9750	86	13524	9750	86
2012	28174	14650	179	28174	14650	179
2013	75864	47690	498	75864	47690	498
2014	139284	63420	958	139284	63420	958
2015	210328	71044	1525	210328	71044	1525
2016	297059	86731	2388	297059	86731	2388
2017	401546	104487	3645	401546	104487	3645
2018	640369	238823	6027	640369	238823	6027
2019	882281	241912	8830	882281	241912	8830
2020	1138654	231088	12003	1138654	231088	12003
2021	2142551	1015900	21131	4612519	3485867	36840
2022	3146449	1025028	31404	8086384	3510705	62922
2023	4475789	1360745	44740	10817357	2793896	85373
2024	6148270	1717221	64699	13893446	3161461	124397
2025	8202734	2119163	114355	17314649	3545601	182427
2026	10678022	2589643	149939	21080968	3948746	251430
2027	13612976	3084893	197300	25192402	4362864	341680
2028	17046439	3630762	269970	29648951	4798229	448285
2029	21017251	4240783	359578	34450615	5249949	572835
2030	25564255	4906582	528400	39597394	5719614	717876
2031	30726293	5690438	661331	45089288	6209770	887475
2032	36542205	6477244	804955	50926297	6724484	1072747
2033	43050835	7313585	1026321	57108422	7254872	1318539

Table 9: US EV passenger car stock, sales, and retirements for Scenarios 1 and 2

2034	50291024	8266509	1286826	63635661	7845779	1630369
2035	58301613	9297416	1565781	70508016	8502723	1957937
2036	67121445	10385613	1901342	77725486	9175406	2285793
2037	76789361	11569258	2297227	85288071	9848377	2622326
2038	87344203	12852069	2744290	93195771	10530026	2973095
2039	98824813	14224900	3178780	101448586	11225910	3338547
2040	111270032	15623999	3646176	110046516	11936477	3720043
2041	124718704	17094848	4121221	118989561	12663088	4119320
2042	139209668	18612185	4789970	128277721	13407480	4536470
2043	154781767	20362069	5514287	137910997	14169745	4974776
2044	171473844	22206363	6159107	147889388	14953166	5433270
2045	189324739	24010002	6793200	158212893	15756775	5911080
2046	208373294	25841756	7463396	168881514	16579701	6409245
2047	228658352	27748453	8195278	179895250	17422980	6931755
2048	250218754	29755680	8992740	191254101	18290606	7484663
2049	273093342	31867328	9858715	202958067	19188629	8051033
2050	297320957	34086330	11018026	215118347	20211313	8638164

Table 10: US EV passenger car stock, sales, and retirements for Scenarios 3 and 4

	Scenario 3			Scenario 4		
Year	EV Stock	EVs Sold	EVs Retired	EV Stock	EVs Sold	EVs Retired
2010	3774	3774	24	3774	3774	24
2011	13524	9750	86	13524	9750	86
2012	28174	14650	179	28174	14650	179
2013	75864	47690	498	75864	47690	498
2014	139284	63420	958	139284	63420	958
2015	210328	71044	1525	210328	71044	1525
2016	297059	86731	2388	297059	86731	2388
2017	401546	104487	3645	401546	104487	3645
2018	640369	238823	6027	640369	238823	6027
2019	882281	241912	8830	882281	241912	8830
2020	1138654	231088	12003	1138654	231088	12003
2021	3588676	2462025	30328	2350164	1223512	22452
2022	6038698	2480351	49858	3561674	1233961	34054
2023	8002505	2013664	67346	4597462	1069842	45539
2024	10210648	2275489	96640	5755676	1203753	63063
2025	12663126	2549119	139420	7036316	1343703	87394
2026	15359940	2836234	190333	8439382	1490461	116424
2027	18301090	3131483	256321	9964874	1641917	153065
2028	21486576	3441807	334000	11612793	1800984	195751
2029	24916398	3763821	424431	13383138	1966096	244910
2030	28590556	4098588	529850	15275908	2137681	302400
2031	32509049	4448343	653033	17291105	2317597	369435
2032	36671878	4815862	787290	19428728	2507058	441982
2033	41079043	5194456	963138	21688778	2702031	533220

Table 10: US EV passenger car stock, sales, and retirements for Scenarios 3 and 4

2034	45730544	5614639	1184312	24071253	2915695	644729
2035	50626381	6080148	1416725	26576154	3149631	762036
2036	55766554	6556897	1649959	29203482	3389364	880809
2037	61151062	7034467	1889660	31953236	3630563	1003375
2038	66779906	7518504	2139585	34825415	3875555	1131312
2039	72653086	8012765	2400025	37820021	4125918	1264723
2040	78770602	8517541	2671983	40937053	4381755	1404175
2041	85132454	9033834	2956604	44176512	4643634	1550100
2042	91738642	9562791	3253912	47538396	4911984	1702439
2043	98589165	10104435	3566428	51022706	5186750	1862792
2044	105684024	10661288	3893192	54629443	5469529	2030206
2045	113023219	11232387	4233544	58358606	5759369	2204278
2046	120606750	11817075	4588281	62210195	6055866	2385516
2047	128434617	12416148	4960223	66184210	6359531	2575320
2048	136506820	13032426	5354538	70280651	6671761	2777788
2049	144823358	13671076	5757673	74499518	6996655	2983463
2050	153459847	14394162	6174782	78873382	7357327	3194901

US EV Lithium Demand Results

Bus Lithium Demand

Table 11: Lithium demand (kg) by year for US school and transit buses

	School bus lithium (kg) demand by transport future scenario				Transit bus lithium (kg) demand by transport future scenario			
Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
2020	1.42E+04	1.42E+04	1.42E+04	1.42E+04	1.30E+06	2.27E+06	1.64E+06	1.61E+06
2021	5.29E+05	5.29E+05	5.29E+05	5.40E+05	1.36E+06	2.57E+06	1.79E+06	1.76E+06
2022	2.30E+05	2.30E+05	2.30E+05	2.35E+05	1.41E+06	2.87E+06	1.93E+06	1.91E+06
2023	2.40E+05	2.40E+05	2.40E+05	2.46E+05	1.47E+06	3.17E+06	2.07E+06	2.06E+06
2024	2.51E+05	2.51E+05	2.51E+05	2.57E+05	2.53E+06	4.48E+06	3.23E+06	3.21E+06
2025	2.63E+05	2.63E+05	2.63E+05	2.69E+05	2.64E+06	5.08E+06	3.52E+06	3.51E+06
2026	2.77E+05	2.77E+05	2.77E+05	2.82E+05	2.76E+06	5.68E+06	3.80E+06	3.80E+06
2027	2.91E+05	2.91E+05	2.91E+05	2.95E+05	1.29E+06	2.03E+06	1.57E+06	1.49E+06
2028	3.07E+05	3.07E+05	3.07E+05	3.09E+05	1.35E+06	2.34E+06	1.71E+06	1.64E+06
2029	3.25E+05	3.25E+05	3.25E+05	3.24E+05	1.40E+06	2.64E+06	1.86E+06	1.79E+06
2030	4.80E+05	4.80E+05	4.80E+05	4.78E+05	1.48E+06	2.97E+06	2.04E+06	1.96E+06
2031	5.05E+05	5.05E+05	5.05E+05	4.98E+05	2.55E+06	4.29E+06	3.20E+06	3.12E+06
2032	5.34E+05	5.34E+05	5.34E+05	5.21E+05	2.66E+06	4.90E+06	3.50E+06	3.42E+06
2033	5.68E+05	5.68E+05	5.68E+05	5.48E+05	2.77E+06	5.51E+06	3.80E+06	3.72E+06
2034	6.04E+05	6.04E+05	6.04E+05	5.76E+05	2.89E+06	6.12E+06	4.10E+06	4.02E+06
2035	6.43E+05	6.43E+05	6.43E+05	6.04E+05	1.42E+06	2.49E+06	1.88E+06	1.72E+06
2036	6.84E+05	6.84E+05	6.84E+05	6.34E+05	1.48E+06	2.81E+06	2.05E+06	1.87E+06
2037	7.28E+05	7.28E+05	7.28E+05	6.64E+05	1.57E+06	3.16E+06	2.25E+06	2.05E+06
2038	7.76E+05	7.76E+05	7.76E+05	6.96E+05	1.63E+06	3.49E+06	2.42E+06	2.21E+06
2039	8.26E+05	8.26E+05	8.26E+05	7.29E+05	2.70E+06	4.83E+06	3.62E+06	3.38E+06
2040	8.80E+05	8.80E+05	8.80E+05	7.62E+05	2.83E+06	5.47E+06	3.95E+06	3.69E+06

Table 11: Lithium demand (kg) by year for US school and transit buses

2041	9.33E+05	9.33E+05	9.33E+05	7.93E+05	2.95E+06	6.11E+06	4.28E+06	4.01E+06
2042	1.51E+06	1.51E+06	1.51E+06	1.35E+06	1.50E+06	2.51E+06	2.10E+06	1.72E+06
2043	1.27E+06	1.27E+06	1.27E+06	1.09E+06	1.57E+06	2.87E+06	2.31E+06	1.89E+06
2044	1.35E+06	1.35E+06	1.35E+06	1.13E+06	1.65E+06	3.23E+06	2.52E+06	2.07E+06
2045	1.64E+06	1.64E+06	1.64E+06	1.37E+06	1.79E+06	3.69E+06	2.84E+06	2.32E+06
2046	1.74E+06	1.74E+06	1.74E+06	1.43E+06	2.88E+06	5.09E+06	4.09E+06	3.53E+06
2047	1.85E+06	1.85E+06	1.85E+06	1.50E+06	3.03E+06	5.79E+06	4.49E+06	3.88E+06
2048	1.97E+06	1.97E+06	1.97E+06	1.56E+06	3.18E+06	6.49E+06	4.90E+06	4.24E+06
2049	2.09E+06	2.09E+06	2.09E+06	1.63E+06	3.34E+06	7.21E+06	5.32E+06	4.61E+06
2050	2.22E+06	2.22E+06	2.22E+06	1.71E+06	1.92E+06	3.70E+06	3.23E+06	1.60E+07
Cumulative (2050)	2.65E+07	2.65E+07	2.65E+07	2.30E+07	6.53E+07	1.26E+08	9.20E+07	9.82E+07

Passenger Vehicle Demand

Table 12: Lithium demand (kg) for US passenger vehicles assuming an 8-year warranty period

	Total Li (kg) demand assuming 8-year battery warranty and small battery scenario				Total Li (kg) demand assuming 8-year battery warranty and medium battery scenario				Total Li (kg) demand assuming 8-year battery warranty and large battery scenario			
Year	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
2020	2.71E+06	3.68E+06	3.06E+06	3.02E+06	3.32E+06	4.29E+06	3.66E+06	3.63E+06	4.51E+06	5.48E+06	4.86E+06	4.82E+06
2021	8.02E+06	2.42E+07	1.72E+07	9.69E+06	1.07E+07	3.33E+07	2.37E+07	1.29E+07	1.59E+07	5.13E+07	3.64E+07	1.92E+07
2022	7.84E+06	2.43E+07	1.71E+07	9.60E+06	1.05E+07	3.35E+07	2.37E+07	1.28E+07	1.58E+07	5.17E+07	3.65E+07	1.92E+07
2023	9.93E+06	2.03E+07	1.45E+07	8.77E+06	1.35E+07	2.76E+07	1.98E+07	1.16E+07	2.05E+07	4.21E+07	3.02E+07	1.71E+07
2024	1.32E+07	2.38E+07	1.72E+07	1.07E+07	1.77E+07	3.21E+07	2.32E+07	1.39E+07	2.65E+07	4.85E+07	3.50E+07	2.01E+07
2025	1.57E+07	2.68E+07	1.92E+07	1.19E+07	2.13E+07	3.61E+07	2.59E+07	1.54E+07	3.22E+07	5.44E+07	3.91E+07	2.24E+07
2026	1.87E+07	2.98E+07	2.12E+07	1.31E+07	2.55E+07	4.02E+07	2.87E+07	1.70E+07	3.89E+07	6.06E+07	4.33E+07	2.47E+07
2027	2.02E+07	2.87E+07	2.08E+07	1.17E+07	2.83E+07	4.02E+07	2.90E+07	1.60E+07	4.43E+07	6.28E+07	4.52E+07	2.45E+07
2028	2.36E+07	3.17E+07	2.29E+07	1.29E+07	3.32E+07	4.44E+07	3.19E+07	1.76E+07	5.19E+07	6.92E+07	4.98E+07	2.70E+07
2029	2.74E+07	3.49E+07	2.51E+07	1.41E+07	3.86E+07	4.88E+07	3.50E+07	1.93E+07	6.05E+07	7.61E+07	5.46E+07	2.95E+07
2030	3.17E+07	3.82E+07	2.74E+07	1.54E+07	4.46E+07	5.33E+07	3.83E+07	2.11E+07	7.00E+07	8.31E+07	5.96E+07	3.22E+07
2031	3.75E+07	4.25E+07	3.07E+07	1.77E+07	5.25E+07	5.89E+07	4.25E+07	2.38E+07	8.20E+07	9.11E+07	6.56E+07	3.58E+07
2032	4.24E+07	4.63E+07	3.33E+07	1.92E+07	5.95E+07	6.40E+07	4.60E+07	2.58E+07	9.31E+07	9.89E+07	7.10E+07	3.88E+07
2033	4.77E+07	5.01E+07	3.59E+07	2.07E+07	6.69E+07	6.93E+07	4.96E+07	2.78E+07	1.05E+08	1.07E+08	7.66E+07	4.19E+07
2034	5.36E+07	5.44E+07	3.88E+07	2.23E+07	7.54E+07	7.51E+07	5.36E+07	3.00E+07	1.18E+08	1.16E+08	8.28E+07	4.52E+07
2035	5.84E+07	5.48E+07	3.95E+07	2.15E+07	8.29E+07	7.72E+07	5.55E+07	2.98E+07	1.31E+08	1.21E+08	8.71E+07	4.61E+07
2036	6.52E+07	5.92E+07	4.26E+07	2.31E+07	9.25E+07	8.35E+07	5.99E+07	3.21E+07	1.46E+08	1.31E+08	9.40E+07	4.97E+07
2037	7.25E+07	6.37E+07	4.57E+07	2.48E+07	1.03E+08	8.97E+07	6.43E+07	3.44E+07	1.63E+08	1.41E+08	1.01E+08	5.32E+07
2038	8.04E+07	6.83E+07	4.89E+07	2.65E+07	1.14E+08	9.61E+07	6.88E+07	3.67E+07	1.81E+08	1.51E+08	1.08E+08	5.68E+07
2039	8.99E+07	7.39E+07	5.31E+07	2.92E+07	1.27E+08	1.04E+08	7.43E+07	4.01E+07	2.01E+08	1.62E+08	1.16E+08	6.15E+07
2040	9.85E+07	7.89E+07	5.66E+07	3.11E+07	1.40E+08	1.10E+08	7.91E+07	4.27E+07	2.21E+08	1.72E+08	1.23E+08	6.55E+07
2041	1.08E+08	8.40E+07	6.01E+07	3.30E+07	1.53E+08	1.17E+08	8.40E+07	4.53E+07	2.41E+08	1.83E+08	1.31E+08	6.94E+07
2042	1.16E+08	8.55E+07	6.18E+07	3.29E+07	1.65E+08	1.21E+08	8.70E+07	4.59E+07	2.62E+08	1.91E+08	1.37E+08	7.15E+07

Table 12: Lithium demand (kg) for US passenger vehicles assuming an 8-year warranty period

2043	1.26E+08	9.03E+07	6.50E+07	3.45E+07	1.80E+08	1.28E+08	9.17E+07	4.82E+07	2.86E+08	2.01E+08	1.44E+08	7.52E+07
2044	1.38E+08	9.55E+07	6.87E+07	3.65E+07	1.96E+08	1.35E+08	9.69E+07	5.09E+07	3.12E+08	2.13E+08	1.52E+08	7.94E+07
2045	1.49E+08	1.01E+08	7.28E+07	3.87E+07	2.13E+08	1.43E+08	1.02E+08	5.40E+07	3.37E+08	2.25E+08	1.61E+08	8.39E+07
2046	1.62E+08	1.08E+08	7.77E+07	4.18E+07	2.30E+08	1.52E+08	1.09E+08	5.78E+07	3.64E+08	2.38E+08	1.70E+08	8.93E+07
2047	1.73E+08	1.14E+08	8.19E+07	4.41E+07	2.47E+08	1.60E+08	1.15E+08	6.09E+07	3.91E+08	2.50E+08	1.79E+08	9.40E+07
2048	1.86E+08	1.20E+08	8.62E+07	4.64E+07	2.65E+08	1.68E+08	1.21E+08	6.40E+07	4.19E+08	2.63E+08	1.88E+08	9.88E+07
2049	1.99E+08	1.26E+08	9.06E+07	4.88E+07	2.83E+08	1.77E+08	1.27E+08	6.73E+07	4.49E+08	2.77E+08	1.98E+08	1.04E+08
2050	2.11E+08	1.29E+08	9.30E+07	6.25E+07	3.01E+08	1.82E+08	1.31E+08	8.19E+07	4.79E+08	2.88E+08	2.06E+08	1.20E+08
Cumulative (2050)	2.39E+09	1.93E+09	1.39E+09	7.76E+08	3.39E+09	2.70E+09	1.94E+09	1.06E+09	5.36E+09	4.23E+09	3.03E+09	1.62E+09

Table 13: Lithium demand (kg) for US passenger vehicles assuming a 10-year warranty period

	Total Li (kg) demand assuming 10-year battery warranty and small battery scenario				Total Li (kg) demand assuming 10-year battery warranty and medium battery scenario				Total Li (kg) demand assuming 10-year battery warranty and large battery scenario			
Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
2020	2.71E+06	3.68E+06	3.06E+06	3.02E+06	3.32E+06	4.29E+06	3.66E+06	3.63E+06	4.51E+06	5.49E+06	4.86E+06	4.83E+06
2021	8.02E+06	2.42E+07	1.72E+07	9.69E+06	1.07E+07	3.33E+07	2.37E+07	1.29E+07	1.59E+07	5.13E+07	3.64E+07	1.92E+07
2022	7.84E+06	2.43E+07	1.71E+07	9.60E+06	1.05E+07	3.35E+07	2.37E+07	1.28E+07	1.58E+07	5.17E+07	3.65E+07	1.92E+07
2023	9.94E+06	2.03E+07	1.45E+07	8.78E+06	1.35E+07	2.76E+07	1.98E+07	1.16E+07	2.06E+07	4.21E+07	3.02E+07	1.71E+07
2024	1.32E+07	2.38E+07	1.72E+07	1.08E+07	1.77E+07	3.22E+07	2.32E+07	1.39E+07	2.66E+07	4.85E+07	3.50E+07	2.02E+07
2025	1.57E+07	2.68E+07	1.92E+07	1.19E+07	2.13E+07	3.61E+07	2.59E+07	1.55E+07	3.23E+07	5.44E+07	3.91E+07	2.24E+07
2026	1.87E+07	2.98E+07	2.13E+07	1.31E+07	2.55E+07	4.02E+07	2.87E+07	1.71E+07	3.89E+07	6.07E+07	4.34E+07	2.48E+07
2027	2.03E+07	2.88E+07	2.08E+07	1.18E+07	2.84E+07	4.02E+07	2.91E+07	1.61E+07	4.44E+07	6.28E+07	4.53E+07	2.46E+07
2028	2.37E+07	3.18E+07	2.29E+07	1.29E+07	3.32E+07	4.44E+07	3.20E+07	1.77E+07	5.21E+07	6.94E+07	4.99E+07	2.71E+07
2029	2.75E+07	3.50E+07	2.51E+07	1.41E+07	3.86E+07	4.89E+07	3.51E+07	1.93E+07	6.07E+07	7.62E+07	5.47E+07	2.96E+07
2030	3.18E+07	3.85E+07	2.77E+07	1.56E+07	4.48E+07	5.38E+07	3.86E+07	2.13E+07	7.03E+07	8.38E+07	6.01E+07	3.25E+07
2031	3.78E+07	4.33E+07	3.13E+07	1.80E+07	5.28E+07	6.00E+07	4.33E+07	2.42E+07	8.25E+07	9.30E+07	6.69E+07	3.65E+07
2032	4.27E+07	4.70E+07	3.38E+07	1.94E+07	5.99E+07	6.51E+07	4.68E+07	2.62E+07	9.37E+07	1.01E+08	7.22E+07	3.94E+07
2033	4.80E+07	5.08E+07	3.64E+07	2.09E+07	6.74E+07	7.03E+07	5.03E+07	2.82E+07	1.06E+08	1.09E+08	7.77E+07	4.24E+07
2034	5.40E+07	5.52E+07	3.94E+07	2.26E+07	7.60E+07	7.62E+07	5.44E+07	3.04E+07	1.19E+08	1.18E+08	8.41E+07	4.58E+07
2035	5.90E+07	5.56E+07	4.01E+07	2.18E+07	8.37E+07	7.85E+07	5.64E+07	3.02E+07	1.32E+08	1.23E+08	8.85E+07	4.69E+07
2036	6.58E+07	6.02E+07	4.33E+07	2.35E+07	9.34E+07	8.48E+07	6.09E+07	3.26E+07	1.48E+08	1.33E+08	9.55E+07	5.05E+07
2037	7.32E+07	6.48E+07	4.65E+07	2.52E+07	1.04E+08	9.12E+07	6.54E+07	3.49E+07	1.65E+08	1.43E+08	1.03E+08	5.41E+07
2038	8.13E+07	6.94E+07	4.97E+07	2.69E+07	1.16E+08	9.77E+07	6.99E+07	3.73E+07	1.83E+08	1.53E+08	1.10E+08	5.78E+07
2039	9.09E+07	7.51E+07	5.40E+07	2.97E+07	1.29E+08	1.05E+08	7.56E+07	4.08E+07	2.04E+08	1.65E+08	1.18E+08	6.26E+07
2040	9.97E+07	8.03E+07	5.76E+07	3.16E+07	1.41E+08	1.12E+08	8.05E+07	4.34E+07	2.24E+08	1.76E+08	1.26E+08	6.66E+07
2041	1.09E+08	8.55E+07	6.12E+07	3.36E+07	1.55E+08	1.20E+08	8.55E+07	4.61E+07	2.45E+08	1.87E+08	1.33E+08	7.07E+07
2042	1.18E+08	8.71E+07	6.29E+07	3.35E+07	1.67E+08	1.23E+08	8.87E+07	4.68E+07	2.65E+08	1.94E+08	1.39E+08	7.28E+07
2043	1.28E+08	9.20E+07	6.63E+07	3.52E+07	1.83E+08	1.30E+08	9.35E+07	4.92E+07	2.90E+08	2.05E+08	1.47E+08	7.67E+07

Table 13: Lithium demand (kg) for US passenger vehicles assuming a 10-year warranty period

2044	1.40E+08	9.74E+07	7.00E+07	3.72E+07	1.99E+08	1.38E+08	9.88E+07	5.19E+07	3.16E+08	2.17E+08	1.55E+08	8.10E+07
2045	1.51E+08	1.03E+08	7.42E+07	3.95E+07	2.16E+08	1.46E+08	1.05E+08	5.50E+07	3.42E+08	2.29E+08	1.64E+08	8.56E+07
2046	1.64E+08	1.10E+08	7.93E+07	4.26E+07	2.33E+08	1.55E+08	1.11E+08	5.90E+07	3.70E+08	2.43E+08	1.74E+08	9.12E+07
2047	1.76E+08	1.16E+08	8.35E+07	4.49E+07	2.51E+08	1.63E+08	1.17E+08	6.21E+07	3.97E+08	2.56E+08	1.83E+08	9.59E+07
2048	1.89E+08	1.22E+08	8.79E+07	4.73E+07	2.69E+08	1.72E+08	1.23E+08	6.54E+07	4.26E+08	2.69E+08	1.93E+08	1.01E+08
2049	2.02E+08	1.29E+08	9.25E+07	4.98E+07	2.88E+08	1.81E+08	1.29E+08	6.87E+07	4.57E+08	2.83E+08	2.02E+08	1.06E+08
2050	2.15E+08	1.32E+08	9.51E+07	6.35E+07	3.07E+08	1.86E+08	1.34E+08	8.34E+07	4.87E+08	2.94E+08	2.11E+08	1.23E+08
Cumulative (2050)	2.42E+09	1.96E+09	1.41E+09	7.88E+08	3.44E+09	2.75E+09	1.97E+09	1.08E+09	5.43E+09	4.30E+09	3.08E+09	1.65E+09

Table 14: Lithium demand (kg) for US passenger vehicles assuming a 12-year warranty period

	Total Li (kg) demand assuming 12-year battery warranty and small battery scenario				Total Li (kg) demand assuming 12-year battery warranty and medium battery scenario				Total Li (kg) demand assuming 12-year battery warranty and large battery scenario			
Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
2020	2.71E+06	3.68E+06	3.06E+06	3.02E+06	3.32E+06	4.29E+06	3.66E+06	3.63E+06	4.51E+06	5.49E+06	4.86E+06	4.83E+06
2021	8.03E+06	2.42E+07	1.72E+07	9.69E+06	1.07E+07	3.33E+07	2.37E+07	1.29E+07	1.59E+07	5.13E+07	3.64E+07	1.92E+07
2022	7.85E+06	2.43E+07	1.72E+07	9.61E+06	1.05E+07	3.35E+07	2.37E+07	1.29E+07	1.58E+07	5.17E+07	3.65E+07	1.92E+07
2023	9.95E+06	2.03E+07	1.45E+07	8.79E+06	1.35E+07	2.76E+07	1.98E+07	1.16E+07	2.06E+07	4.21E+07	3.02E+07	1.72E+07
2024	1.32E+07	2.39E+07	1.73E+07	1.08E+07	1.77E+07	3.22E+07	2.33E+07	1.40E+07	2.66E+07	4.85E+07	3.50E+07	2.02E+07
2025	1.58E+07	2.68E+07	1.92E+07	1.20E+07	2.14E+07	3.62E+07	2.60E+07	1.55E+07	3.24E+07	5.45E+07	3.92E+07	2.25E+07
2026	1.88E+07	2.99E+07	2.13E+07	1.32E+07	2.56E+07	4.03E+07	2.88E+07	1.71E+07	3.90E+07	6.08E+07	4.35E+07	2.49E+07
2027	2.03E+07	2.88E+07	2.09E+07	1.18E+07	2.85E+07	4.03E+07	2.92E+07	1.62E+07	4.45E+07	6.30E+07	4.54E+07	2.47E+07
2028	2.37E+07	3.18E+07	2.30E+07	1.30E+07	3.33E+07	4.45E+07	3.21E+07	1.78E+07	5.22E+07	6.95E+07	5.01E+07	2.72E+07
2029	2.76E+07	3.51E+07	2.52E+07	1.42E+07	3.88E+07	4.90E+07	3.53E+07	1.95E+07	6.09E+07	7.64E+07	5.50E+07	2.99E+07
2030	3.20E+07	3.87E+07	2.78E+07	1.57E+07	4.50E+07	5.40E+07	3.88E+07	2.15E+07	7.06E+07	8.41E+07	6.05E+07	3.29E+07
2031	3.79E+07	4.35E+07	3.14E+07	1.81E+07	5.31E+07	6.03E+07	4.35E+07	2.44E+07	8.29E+07	9.33E+07	6.72E+07	3.69E+07
2032	4.31E+07	4.80E+07	3.45E+07	1.98E+07	6.04E+07	6.65E+07	4.78E+07	2.68E+07	9.45E+07	1.03E+08	7.39E+07	4.04E+07
2033	4.87E+07	5.31E+07	3.80E+07	2.18E+07	6.84E+07	7.36E+07	5.27E+07	2.94E+07	1.07E+08	1.14E+08	8.15E+07	4.43E+07
2034	5.48E+07	5.73E+07	4.09E+07	2.34E+07	7.71E+07	7.93E+07	5.66E+07	3.15E+07	1.21E+08	1.23E+08	8.75E+07	4.76E+07
2035	6.00E+07	5.76E+07	4.15E+07	2.25E+07	8.51E+07	8.12E+07	5.84E+07	3.13E+07	1.35E+08	1.28E+08	9.17E+07	4.86E+07
2036	6.70E+07	6.24E+07	4.48E+07	2.43E+07	9.52E+07	8.80E+07	6.31E+07	3.38E+07	1.51E+08	1.38E+08	9.91E+07	5.24E+07
2037	7.48E+07	6.72E+07	4.82E+07	2.61E+07	1.06E+08	9.48E+07	6.79E+07	3.63E+07	1.68E+08	1.49E+08	1.07E+08	5.63E+07
2038	8.31E+07	7.21E+07	5.17E+07	2.79E+07	1.18E+08	1.02E+08	7.27E+07	3.88E+07	1.87E+08	1.60E+08	1.14E+08	6.02E+07
2039	9.31E+07	7.81E+07	5.62E+07	3.08E+07	1.32E+08	1.10E+08	7.87E+07	4.24E+07	2.09E+08	1.72E+08	1.23E+08	6.52E+07
2040	1.02E+08	8.36E+07	5.99E+07	3.28E+07	1.45E+08	1.17E+08	8.39E+07	4.52E+07	2.29E+08	1.83E+08	1.31E+08	6.94E+07
2041	1.12E+08	8.91E+07	6.38E+07	3.49E+07	1.59E+08	1.25E+08	8.92E+07	4.80E+07	2.51E+08	1.95E+08	1.39E+08	7.38E+07
2042	1.21E+08	9.10E+07	6.57E+07	3.50E+07	1.72E+08	1.29E+08	9.27E+07	4.89E+07	2.73E+08	2.03E+08	1.46E+08	7.62E+07
2043	1.32E+08	9.63E+07	6.93E+07	3.67E+07	1.88E+08	1.36E+08	9.79E+07	5.14E+07	2.99E+08	2.15E+08	1.54E+08	8.03E+07

Table 14: Lithium demand (kg) for US passenger vehicles assuming a 12-year warranty period

2044	1.44E+08	1.02E+08	7.33E+07	3.89E+07	2.06E+08	1.44E+08	1.04E+08	5.44E+07	3.27E+08	2.28E+08	1.63E+08	8.49E+07
2045	1.57E+08	1.08E+08	7.78E+07	4.13E+07	2.23E+08	1.53E+08	1.10E+08	5.77E+07	3.54E+08	2.41E+08	1.72E+08	8.98E+07
2046	1.70E+08	1.15E+08	8.31E+07	4.46E+07	2.42E+08	1.62E+08	1.17E+08	6.18E+07	3.83E+08	2.55E+08	1.83E+08	9.57E+07
2047	1.83E+08	1.22E+08	8.77E+07	4.71E+07	2.60E+08	1.71E+08	1.23E+08	6.52E+07	4.12E+08	2.69E+08	1.93E+08	1.01E+08
2048	1.96E+08	1.28E+08	9.24E+07	4.96E+07	2.79E+08	1.81E+08	1.30E+08	6.87E+07	4.43E+08	2.83E+08	2.03E+08	1.06E+08
2049	2.10E+08	1.35E+08	9.73E+07	5.23E+07	3.00E+08	1.90E+08	1.36E+08	7.23E+07	4.75E+08	2.98E+08	2.13E+08	1.12E+08
2050	2.24E+08	1.39E+08	1.00E+08	6.61E+07	3.19E+08	1.97E+08	1.41E+08	8.72E+07	5.07E+08	3.10E+08	2.22E+08	1.29E+08
Cumulative (2050)	2.49E+09	2.04E+09	1.46E+09	8.16E+08	3.54E+09	2.86E+09	2.05E+09	1.12E+09	5.59E+09	4.47E+09	3.20E+09	1.71E+09

Table 15: Material demand, recycled material available, and net demand (material demand - recycled material available) assuming a medium battery capacity future and an 8-year warranty period

	Scenario 1			Scenario 2			Scenario 3			Scenario 4		
Year	Demand	Recycled material available	Net demand	Demand	Recycled material available	Net demand	Demand	Recycled material available	Net demand	Demand	Recycled material available	Net demand
2020	4.6E+06	1.3E+06	3.3E+06	6.6E+06	2.3E+06	4.3E+06	5.3E+06	1.7E+06	3.7E+06	5.3E+06	1.7E+06	3.6E+06
2021	1.2E+07	1.5E+06	1.1E+07	4.6E+07	2.8E+06	4.3E+07	3.2E+07	2.0E+06	3.0E+07	1.8E+07	1.9E+06	1.6E+07
2022	1.2E+07	1.6E+06	1.1E+07	2.7E+07	3.3E+06	2.4E+07	2.0E+07	2.3E+06	1.7E+07	1.2E+07	2.2E+06	1.0E+07
2023	1.5E+07	1.8E+06	1.3E+07	3.1E+07	3.8E+06	2.7E+07	2.2E+07	2.6E+06	1.9E+07	1.4E+07	2.4E+06	1.1E+07
2024	2.0E+07	2.1E+06	1.8E+07	3.7E+07	4.5E+06	3.2E+07	2.7E+07	3.0E+06	2.4E+07	1.7E+07	2.8E+06	1.5E+07
2025	2.4E+07	2.6E+06	2.2E+07	4.1E+07	5.3E+06	3.6E+07	3.0E+07	3.6E+06	2.6E+07	1.9E+07	3.2E+06	1.6E+07
2026	2.9E+07	3.0E+06	2.6E+07	4.6E+07	6.3E+06	4.0E+07	3.3E+07	4.2E+06	2.9E+07	2.1E+07	3.6E+06	1.8E+07
2027	3.0E+07	2.0E+06	2.8E+07	4.3E+07	3.4E+06	3.9E+07	3.1E+07	2.6E+06	2.8E+07	1.8E+07	1.6E+06	1.6E+07
2028	3.5E+07	2.8E+06	3.2E+07	4.7E+07	4.5E+06	4.3E+07	3.4E+07	3.4E+06	3.1E+07	2.0E+07	2.1E+06	1.7E+07
2029	4.0E+07	3.8E+06	3.7E+07	5.2E+07	5.9E+06	4.6E+07	3.7E+07	4.5E+06	3.3E+07	2.1E+07	2.8E+06	1.9E+07
2030	4.7E+07	5.5E+06	4.1E+07	5.7E+07	7.7E+06	4.9E+07	4.1E+07	5.9E+06	3.5E+07	2.4E+07	3.6E+06	2.0E+07
2031	5.6E+07	8.0E+06	4.8E+07	6.4E+07	1.1E+07	5.3E+07	4.6E+07	8.6E+06	3.8E+07	2.7E+07	5.6E+06	2.2E+07
2032	6.3E+07	9.9E+06	5.3E+07	6.9E+07	1.4E+07	5.5E+07	5.0E+07	1.1E+07	3.9E+07	3.0E+07	6.9E+06	2.3E+07
2033	7.0E+07	1.3E+07	5.8E+07	7.5E+07	1.9E+07	5.6E+07	5.4E+07	1.4E+07	4.0E+07	3.2E+07	8.7E+06	2.3E+07
2034	7.9E+07	1.6E+07	6.3E+07	8.2E+07	2.5E+07	5.7E+07	5.8E+07	1.8E+07	4.0E+07	3.5E+07	1.1E+07	2.4E+07
2035	8.5E+07	2.0E+07	6.5E+07	8.1E+07	3.1E+07	4.9E+07	5.8E+07	2.3E+07	3.5E+07	3.2E+07	1.3E+07	1.9E+07
2036	9.5E+07	2.5E+07	7.0E+07	8.7E+07	3.9E+07	4.8E+07	6.3E+07	2.8E+07	3.5E+07	3.5E+07	1.6E+07	1.9E+07
2037	1.1E+08	3.1E+07	7.4E+07	9.4E+07	4.6E+07	4.7E+07	6.7E+07	3.3E+07	3.4E+07	3.7E+07	1.9E+07	1.9E+07
2038	1.2E+08	3.8E+07	7.9E+07	1.0E+08	5.4E+07	4.7E+07	7.2E+07	3.8E+07	3.4E+07	4.0E+07	2.1E+07	1.8E+07
2039	1.3E+08	4.4E+07	8.6E+07	1.1E+08	6.0E+07	4.9E+07	7.9E+07	4.3E+07	3.6E+07	4.4E+07	2.4E+07	2.1E+07
2040	1.4E+08	5.2E+07	9.2E+07	1.2E+08	6.7E+07	5.0E+07	8.4E+07	4.8E+07	3.6E+07	4.7E+07	2.6E+07	2.1E+07
2041	1.6E+08	6.0E+07	9.6E+07	1.2E+08	7.4E+07	5.1E+07	8.9E+07	5.3E+07	3.6E+07	5.0E+07	2.9E+07	2.1E+07

Table 15: Material demand, recycled material available, and net demand (material demand - recycled material available) assuming a medium battery capacity future and an 8-year warranty period												
2042	1.7E+08	6.9E+07	9.9E+07	1.2E+08	7.7E+07	4.8E+07	9.1E+07	5.5E+07	3.6E+07	4.9E+07	2.9E+07	2.0E+07
2043	1.8E+08	8.0E+07	1.0E+08	1.3E+08	8.4E+07	4.8E+07	9.5E+07	6.0E+07	3.5E+07	5.1E+07	3.2E+07	2.0E+07
2044	2.0E+08	9.0E+07	1.1E+08	1.4E+08	9.2E+07	4.8E+07	1.0E+08	6.6E+07	3.5E+07	5.4E+07	3.4E+07	2.0E+07
2045	2.2E+08	1.0E+08	1.1E+08	1.5E+08	1.0E+08	4.8E+07	1.1E+08	7.2E+07	3.5E+07	5.8E+07	3.7E+07	2.0E+07
2046	2.3E+08	1.1E+08	1.2E+08	1.6E+08	1.1E+08	4.9E+07	1.1E+08	7.9E+07	3.6E+07	6.3E+07	4.2E+07	2.1E+07
2047	2.5E+08	1.3E+08	1.2E+08	1.7E+08	1.2E+08	4.9E+07	1.2E+08	8.5E+07	3.6E+07	6.6E+07	4.5E+07	2.1E+07
2048	2.7E+08	1.4E+08	1.3E+08	1.8E+08	1.3E+08	4.8E+07	1.3E+08	9.2E+07	3.5E+07	7.0E+07	4.9E+07	2.1E+07
2049	2.9E+08	1.6E+08	1.3E+08	1.9E+08	1.4E+08	4.8E+07	1.3E+08	9.9E+07	3.5E+07	7.4E+07	5.2E+07	2.1E+07
2050	3.1E+08	8.3E+07	2.2E+08	1.9E+08	7.6E+07	1.1E+08	1.4E+08	5.5E+07	8.2E+07	1.0E+08	2.9E+07	7.0E+07
Cumulative (2050)	2.49E+09	2.04E+09	1.46E+09	8.16E+08	3.54E+09	2.86E+09	2.05E+09	1.12E+09	5.59E+09	4.47E+09	3.20E+09	1.71E+09

US EV Lithium Demand Results

Bus Lithium Demand

Table 16: Cumulative lithium circularity potential in 2050 assuming medium battery scenario and eight-year warranty period			
Scenario 1	Scenario 2	Scenario 3	Scenario 4
38%	49%	49%	47%