Future Lithium Demand for a Carbon Free Transportation System in The United States

By

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Abstract

Electric vehicle adoption is increasing rapidly in the United States, driven by policies aimed at mitigating climate change. Lithium-ion batteries are the key enabling technology for EVs. The production and refining of lithium is thus essential to electric vehicle manufacturing. Lithium is considered a critical mineral in the United States because its use is linked to national security, energy and transportation needs and its ease of availability in the future is not guaranteed. Understanding how much lithium is required for a clean transportation future is important to mitigate risks associated with lithium depletion and potential barriers to achieving climate mitigation targets. For this reason, the following thesis models lithium demand and recycling in the United States from 2020 to 2050 under a variety of scenarios that examine vehicle battery size, vehicle ownership rates, and recycling rates to determine the quantity of virgin lithium required for complete electrification of the on-road US fleet by 2050. The model shows that with no significant changes in battery size or mode share US lithium demand will be 300 million kg in 2050 exceeding current global lithium production by 200% and recycled material will not be able to close the gap between future demand and current production. Reducing only battery size can result in up to a 29% decrease in lithium demand while shifting mode shares only can result in a 67% decrease in lithium demand in 2050.

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Introduction

In 2021 President Biden set a target to achieve 50%-52% reduction of 2005 level greenhouse gas pollution by 2030. The White House explored multiple pathways to achieve this goal, including decarbonizing transportation. While there are a variety of ways to decarbonize transportation, batteries are an essential component to most viable alternatives to internal combustion engine vehicles like fuel cell, electric and hybrid vehicles. The dominant battery type, lithium-ion batteries (LIB), require lithium as the name suggests. As the United States (US) transitions to a decarbonized transportation future, the demand for lithium will increase. It is important to understand what that future demand of lithium is, in order to prepare for externalities of deploying a relatively new technology. For example, while electric vehicles may achieve reductions in greenhouse gas emissions on a life cycle basis, the high mineral intensity of LIBs means additional mining, which causes additional impacts for frontline communities and ecosystems near mining sites. These communities are often not those that benefit from new technologies both at global and local scales. The US has the opportunity to not repeat the history of extractive relationships between high-income countries and lower- and middle-income countries, and the disproportionate impact on low-income and indigenous communities from mining in the US [cite the climate and community report and maybe some other good research here about the inequities in impact and access, could even do our UNEP report]. .

Given the urgent need to decarbonize the transport sector, this thesis starts from the assumption that vehicle electrification will occur. What is explored is how much lithium is required for a fully decarbonized transportation future. Thus, it is not a matter of whether vehicle electrification will happen, but how it will occur in the US. This thesis explores the lithium footprint of different pathways for achieving complete electrification of the on-road passenger vehicle fleet by 2050 to understand the policy levers that may be best used to achieve electrification in the US context with the lowest impact to people and planet This thesis constitutes the contributions of the author to the publication More Mobility, Less Mining written with Thea Riofrancos, Alissa Kendall, Matthew Haugen, Batul Hassan, Kira McDonald, and Margaret Slattery.

Review of Literature

Lithium

Lithium is a soft, silver metal that was initially discovered from a mineral. Lithium is used in a variety of products including batteries, ceramics, and pharmaceuticals.[1] Historically, greases, glasses, ceramics made up 40-50% of global lithium consumption.[2] In 2000 global lithium production was less than 20,000 tons, a majority of which went to ceramics, glass and other end uses.[24] By 2021 global lithium production was 100,000 tons, with LIBs making up 81% of demand. The 400% increase in lithium production over the last 2 decades was driven by increasing LIB demand, and as demand for EVs powered by LIBs rises in the coming years and decades, demand for lithium will rise accordingly.

Lithium deposits are typically found in 2 forms, hard rock and brines. A majority of the world's lithium production in 2019 was from 6 hard rock operations in Australia, 1 hard rock operation in China, and 2 brine operations in each in Argentina and Chile.[3] The process of extracting lithium from hard rock deposits and brines varies significantly. Historically, extracting lithium from high-quality brines was more economically feasible due to its low energy requirements. However, as lithium demand and price has increased, the operating cost gap has become less of a concern. Both processes produce lithium-carbonate, the chemical needed in batteries. In order to convert lithium bearing minerals into lithium carbonate, the mineral is crushed, ground and roasted multiple times. The crushed mineral then goes through acid leaching using sulfuric acid before it is polished to remove calcium and magnesium. In order to convert the brine to lithium carbonate, the brine is pumped from underground salt lakes to engineered ponds on the surface. Using solar evaporation, the brine is further concentrated to increase lithium content and decrease water content. Lastly, the concentrated brine undergoes chemical processing to remove impurities.

Lithium resources, rock or brine, are developed through tectonic activity, the presence of Li- bearing rocks (magmatic or sediment), and exposure to moisture (typically ground water or spring water circulation). It is unclear how long these supplies take to replenish. Brines deposits derive from quaternary rock structures, that can be up to 2.5 million years old. Hard rock deposits range in age from the Miocene to Precambrian, and therefore are significantly older. While Li is found in over 100 minerals, 5 are used for commercial hard rock production. These 5 minerals are spodumene, lepidolite, petalite, amblygonite and eucryptite, with spodumene being the most abundant due to its high lithium content (8.1% Li2O).[4] Hard rock deposits are found in several orogenic phases located in various geographies.[5] Parameters that lead to economically viable hard rock lithium deposits are pre-existing Li source, lithospheric thickening, and the existence of fractures to allow for weathering. Unlike hard rock lithium deposits that are found in various geographies, brines are located in arid climates in tectonically affected basins that interact with Li rich rocks (Gutierrez, 2019). The maximum Li concentration found in a brine deposit globally is in the Atacama desert in Chile, where the average Li concentration ranges from 1000 and 6400 mg/L.[6] The minimum concentration of Li in brines considered to have commercial value is 10–20 mg/L.

Effects of Mining

Lithium production raises equity concerns related to land use, water sovereignty and mineral resource distribution. The mining phase, both hard rock mining and brine, require high land use. As lithium demand has increased, so has the pressure to locate new sources of lithium on historically indigenous and rural land in the global south.[7] This land grab can destabilize the social and economic order of already vulnerable communities.[8] Almost 60% of lithium demand is supplied from brines.[9] Lithium production from brine is water intensive, because it requires water to be pumped from the earth and evaporated in pools. The evaporation process decreases local water supply, infringing on the water sovereignty of local communities. In hard rock methods, tailings can spread to local water sources impacting local water chemistry.[10] These water practices can exacerbate existing fractures in indigenous communities. The distribution of lithium resources is unbalanced and extracted minerals from the global south, typically are traded as finished product to mostly global north countries to meet global consumption demand.[11] Considering a significant portion of lithium mining operations occur in the global south and the impacts of mining listed above, there are distributive justice concerns concerning burdens and benefits that need to be explored. Furthermore, countries with critical mineral resources do not typically follow formal regulations regarding resource extraction, inviting foreign private mining for easier, low-cost operations.[12]

Lithium-Ion Battery Technology

LIBs are the most common energy storage technology for EVs due to their high energy density, cycle stability and robustness.[13] The main components of LIBs are the cathode, anode, electrolyte solution and the separator; each component requires a different critical mineral depending on the chemistry of the battery.

Commercially viable LIB anodes typically use graphite, but some battery chemistries use silicon or lithium titanate.[14] Cathodes can use a wider variety of minerals including manganese, cobalt, nickel, aluminum and lithium.[15] 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 Iron Phosphate), and LMO (Lithium Manganese Oxide). 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 cathode 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 or NMC 811) to reduce the amount of cobalt and lithium required. While the combination of many minerals in LIBs varies depending on the chemistry of the battery, lithium is considered not substitutable as it is present in all current chemistries. For example, the battery industry is moving towards cobalt free batteries due to the criticality of the mineral.[14] This has led to the resurgence of LFP and LMO battery chemistries which require no cobalt, but do require lithium. The common battery chemistry types and their mineral weight percent are shown in table 1.

Table 1: Lithium-Ion Battery Pack Composition by Weight (kg/kWh) from Table 2. Dunn et al.

Cathode	Lithium	Nickel	Cobalt	Manganese	Aluminum	Copper	Graphite
NMC111	2.40%	5.90%	5.90%	5.50%	52.40%	11.40%	16.50%
NMC523	2.30%	8.70%	3.50%	4.90%	52.50%	11.30%	16.80%
NMC622	2.10%	9.50%	3.20%	3.00%	54.10%	10.80%	17.20%
NMC811	1.90%	11.40%	1.40%	1.30%	55.40%	10.40%	18.20%
NCA	1.90%	12.50%	2.40%	0.00%	54.40%	10.50%	18.20%
LMO	1.60%	0.00%	0.00%	21.00%	50.70%	13.00%	13.70%
LFP	1.70%	0.00%	0.00%	0.00%	62.40%	16.70%	19.20%

A key issue for LIBs is declining performance over time, largely driven by cycling but also by calendar aging and environmental conditions. Battery condition is represented by the concept of state-of-health (SOH). SOH is a value that "compares the current state of the battery with the state of the battery at the beginning of life."[16] It is calculated by dividing the EV's maximum battery charge by the rated capacity. SOH is difficult to predict because it cannot be measured directly and changes in SOH are the result of complex interactions among factors and processes within the battery. These factors are user-dependent like charging and e/discharging habits, environment-dependent like temperature, or battery-dependent like the initial design capacity.[17] A lower depth of discharge allows batteries to last longer. Keeping the state of charge (SOC), the amount of power available in the battery, high without reaching the maximum battery capacity also allows the battery to last longer. From the perspective of LIBs used in EVs, 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 a LIB. The optimal temperature range for a LIB is 15–35 °C.[18] 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 due to the need for special equipment and experiment conditions. Therefore, most methods to determine SOH are through indirect measurement techniques using health indicators (HI). HIs are historical charging data that are mathematically manipulated to reflect the internal electrochemical reaction indicating the level of battery degradation.[19] Commonly used HIs to determine SOH are internal resistance (IR), temperature, voltage drop, and constant current (CC) charging time. Using IR as the health factor to determine SOH gives accurate early-stage predictions.[20] There is a strong linear relationship between CC charging time and SOH and CC charging time is used as a health factor to determine SOH.[21,22] Voltage drop is also used as a health factor in model-based estimations of SOH.[23]

LIBS are recommended to be replaced in EVs at 80% SOH. There are no federal laws in the US that directly address battery degradation and warranty requirements. However, in August 2022 the California Air and Resources Board (CARB) approved the Advanced Clean Cars II rule, making California the first state in the US 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. Despite the lack of legal incentive, most original equipment manufacturers (OEMs) today provide warranties that cover LIBs for 8 years or 100,000 miles.

EVs in the US

EV sales and registrations have steadily grown each year, barring 2020, in the US.[24] Policy and industry trends indicate that this growth will continue. For example, the Inflation Reduction Act of 2022 gives tax credits to EV consumers and car companies like General Motors and Mercedes are promising to sell only electric cars in the near future. The International Energy Agency (IEA) estimates 6.8 million EV sales in the US in 2030 compared to 800,000 in 2022. EVs are also estimated to be 48% to 61% of total car sales by 2030.[25] An increase in EVs, which require some of the biggest batteries, will cause an increase in lithium demand. Another driving factor for lithium demand is increasing battery sizes. Range anxiety is one of the biggest barriers to EV adoption.[26] In response, car manufacturers have made bigger batteries since the early 2010s. For example, the Nissan Leaf was the most popular EV in the early 2010s and came with a 24 or 30 kWh battery. [27] Now, popular models have bigger batteries driving the sales-weighted average battery capacity of a new EV in the US from 35 kWh in 2012 to just over 70 kWh in 2021. Considering lithium is an essential material in LIBs, bigger batteries will result in a higher lithium demand.

Existing Lithium Demand Forecasting

Previous material flow analyses of lithium are not easy to compare to one another because they represent values for different end uses with different temporal and spatial boundaries. Most MFAs conducted were for historical lithium flows.[28,29,30,31] MFAs that assessed future lithium flows were often limited to LIBs in EVs.[32, 33] Furthermore these studies focused on waste flows from LIBs for recycling potential. In one of these MFAs 20 kt of lithium is the expected waste flow for LIBs in EVs in 2040 cumulatively. In the other MFA 60 kt of lithium can be recovered from LIBs in 2040.[33] MFAs that are future oriented had similar methods for determining lithium demand and recyclability. Future EV sales, battery and/or vehicle lifespan, and lithium content in LIBs were important inputs to the models.

Methods

The lithium demand model uses principles of material flow analysis to estimate the amount of lithium in EV LIBs accumulating and retiring in the United States. The temporal boundaries for this lithium demand model are 2020-2050. Only LIBs in pure EVs, are accounted for since they require the biggest batteries and therefore the most lithium. This means that plug-in hybrid EVs, fuel cell vehicles, and hybrid electric vehicles are omitted from the analysis.

The model estimated lithium demand as a function of EV sales and considered four parameters that shape EV LIB demand: vehicle ownership rates as a function of transportation futures, described in more detail below; battery capacity demand as a function of vehicle design and consumer choices; battery warranty alternatives; and recycling rates. The four transportation futures scenarios were developed by a collaborator on the Climate and Community report which also included the work described in this thesis.[34] The transportation futures scenarios are:

Scenario 1 (S1): This scenario represents the status quo. It models a future with the same vehicle ownership rates as today. In this scenario population growth is the only driver for the change in total vehicle demand.

Scenario 2 (S2): This scenario assumed policy and infrastructure investments to increase the use of active modes of transportation and public transit to reduce the level of car dependence in US cities to the equivalent of comparable cities in the European Union. Mode shares and car ownership rates do not change in rural areas.

Scenario 3 (S3): This scenario builds on scenario two, but assume that more change occurs to land use like denser cities, better infrastructure for active and public transport, and less subsidies for private vehicle ownership like parking. It also accounts for policy and cultural changes that reduce car ownership. Public transit also reduces its lithium intensity per trip by shifting to electrified rail rather than buses.

Scenario 4 (S4): This scenario builds on the shifts described in S2 and S3 in a more ambitious manner. Mode shares reflect the achievement of goals set by cities like Vienna. This means less car use and ownership. Reliance on buses in favor of other transit also decreases in this scenario.

These futures provided a vehicle ownership rate in 2050 that could then be translated into the total US fleet size for on-road passenger vehicles (light duty passenger vehicles and buses). This fleet size was then combined with vehicle retirement rates to infer new vehicle car sales from 2020 to 2050. In order to do this, vehicle retirement rates (i.e. vehicle failures) were estimated using a Weibull distribution assuming an average lifetime of 15 years and using a shape parameter of 7, a method that is used to show increasing wear and failure with time.[35] The Weibull shape parameter was chosen because values over 1 indicate wear out failure.[36] 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:

$$\eta = \frac{t}{e^{\Gamma(1+\frac{1}{\beta})}}$$

Eq 1.

Where t is the average lifetime of a battery, β is the shape parameter and η is the scale parameter. Table A1 in the appendix provides the probability of battery failure over time given by the Weibull distribution. Then, for each new EV sold, material demand is calculated based on the battery size, lifetime, and chemistry.

Figure 1 illustrates the approach to estimate cumulative lithium demand, and the following sections explain the model, data, and assumptions.

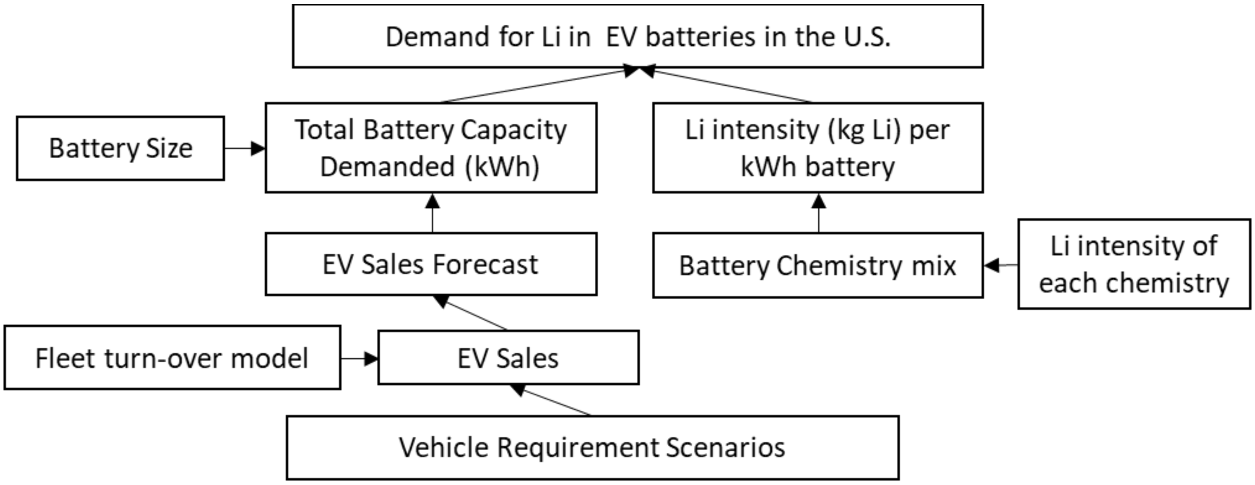


Figure 1: Modeling approach for estimating lithium demand from EVs in the US from Figure 9. Riofrancos et al.

EV Sales Forecast

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 IEA Global EV Outlook, the Bureau of Transportation Statistics and the School Bus Fleet website.[24,37,38] The future vehicle requirement estimates were calculated based on the 2050 vehicle requirements from the decarbonized transportation scenarios. The historical and future projections were then used to estimate total EV requirements between 2021 and 2049. 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.

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 turn-over 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 A8 and A9 in the appendix.

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 and contribute 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. Scenarios for longer warranty periods of 10 and 12 years were also tested, but had a very small effect on cumulative lithium demand and thus are not a focus of analysis.

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 US has increased from about 35 kWh in 2012 to just over 70 kWh in 2021. This means that the average new vehicle has 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. There are 3 different scenarios for modeling the future sales-weighted average battery capacity are modeled based on these values:

- 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-generation Nissan Leaf and the large battery capacity was chosen based on recent electric light trucks like the Ford F-150 Lightning, 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

Since 2018, NCA has represented more than half of the share of batteries in new EV sales in the US, a larger share compared to other countries. This is mainly because Tesla has the highest EV sales in the US and uses almost exclusively NCA batteries. In this study we assume that passenger EV batteries will be 50 percent NCA and 50 percent NMC811 into the future, and E-bus batteries will be 50 percent LFP and 50 percent NMC811, reflecting two popular E-Bus models from makers BYD and Proterra.[39][40]

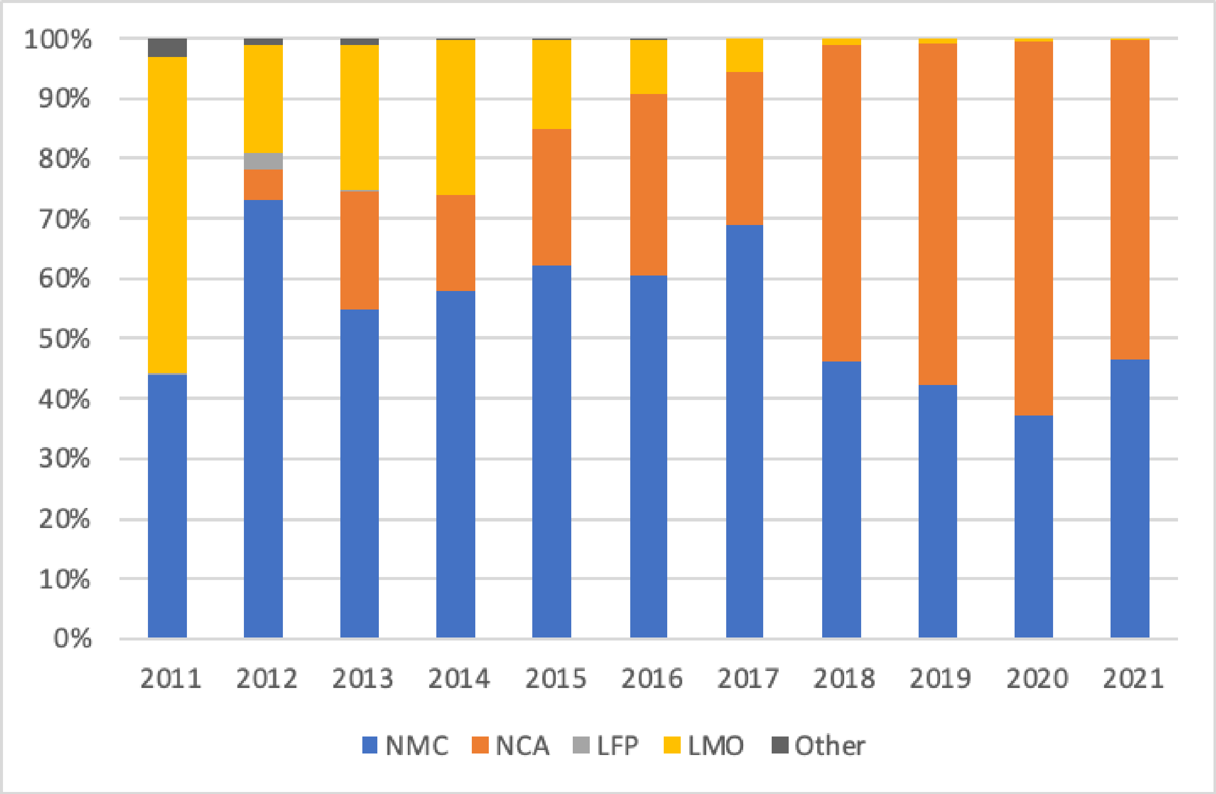


Figure 2. Battery chemistry types in new light duty EV sales in the US (2011-2021)

Bus modeling

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. There are two types of buses are widely used in the US: school buses and transit buses. The same approach for determining bus sales is used as in light duty vehicles, whereby the final bus requirement estimated in the different scenarios for transportation futures is used along with historical bus stock data to estimate the US bus stock between 2010 and 2050. 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 seven year cycles. Transit buses also accrue mileage much faster than school buses and undergo what is known as a “7-year midlife overhaul” during which a bus’s battery pack is assumed to need replacement[41]. Thus the fleet turn-over model assumes a fixed 14-year transit bus lifetime with a 7-year midlife overhaul that includes full battery replacement. Unlike light duty vehicles, we do not model lifetime stochastically, or statistically determined, due to a lack of data on bus survival rates. We assume all e-bus include a 450 kWh hour battery pack based on popular e-bus models from Proterra and BYD”. School buses are, on average, much older than transit buses and are used for many more years. Because they operate few routes per day, they accrue mileage more slowly than active transit buses and, as such, their lifetime in years is longer. 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

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. 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 material recovery. In addition, recycling processes do not necessarily recover all materials. The choice of which materials to recover and at what level is an economic one, and is driven by the value of each material. For example, historically, it has been cheaper to mine new lithium than recycle it, making the recovery of lithium less attractive to recyclers.

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. Additionally, used EV batteries can be repurposed for energy grid storage as they still have significant capacity even when retired from their first use in a vehicle. 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.[42] 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.

Modeled Scenarios

To understand the range of possible demand for lithium we use a scenario analysis approach that combines possible decarbonization pathways (transportation futures), 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 3 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 3. Scenarios included in the assessment.

In the absence of intervention, the most likely scenario seems to be the base case with medium 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 such, 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 tables A2 through A6 of the appendix.

Results

Lithium Demand

Results show that under the base case conditions, cumulative lithium demand by 2050 will be 3,458 Mt. To put this into context, global annual lithium production in 2020 totaled only .082 Mt. Results are very sensitive to scenario choices. For example, when comparing medium batteries in scenario 1 to small batteries in the same scenario, there is a 29% decrease in cumulative and 2050 lithium demand (Figure 5). Conversely, when medium batteries in scenario 1 are compared to large batteries there is a 56% increase in cumulative lithium demand and 58% increase in annual 2050 demand. 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. The results also show a smaller change in demand from extending the warranty period from the standard 8 year to 10 or 12 years. When comparing the cumulative lithium requirement of the medium battery scenario and the common 8 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.

	8 year battery warranty and an average battery capacity of 35 kWh				8 year battery warranty and an average battery capacity of 70 kWh				8 year battery warranty and an average battery capacity of 135 kWh			
	35 kWh battery				70 kWh battery				150 kWh battery			
	1	2	3	4	1	2	3	4	1	2	3	4
assenger cars	394	931	389	76	394	704	941	061	363	225	027	621
ransit Buses	5	26	2	8	5	26	2	8	5	26	2	8
chool Buses	7	7	7	3	7	7	7	3	7	7	7	3

Table 2: Cumulative lithium demand in 2050 measured in megatons

Passenger cars comprised the greatest demand for lithium because more cars than buses are required in every transportation future scenario modeled. Lithium demand from transit buses for the scenarios with the lowest demand (S1) is calculated to be 1.9 million kg and 16 million kg for the highest (S4). School busses require 2.2 million kg of lithium for scenario 1 and 1.7 million kg for scenario 4. 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. For context, private passenger vehicle demand in scenario 1 with an 8 year warranty and medium batteries (301 million kg) is 72 times larger than scenario 1 transit and school busses combined (4.1 million kg). When comparing these same values for scenario 4 the lithium demand for private passenger vehicles is closer to 4 times larger than the demand for busses. These results suggest that reducing demand for private passenger vehicles and maintaining or reducing battery capacity are the most effective pathways to reducing future lithium demand.

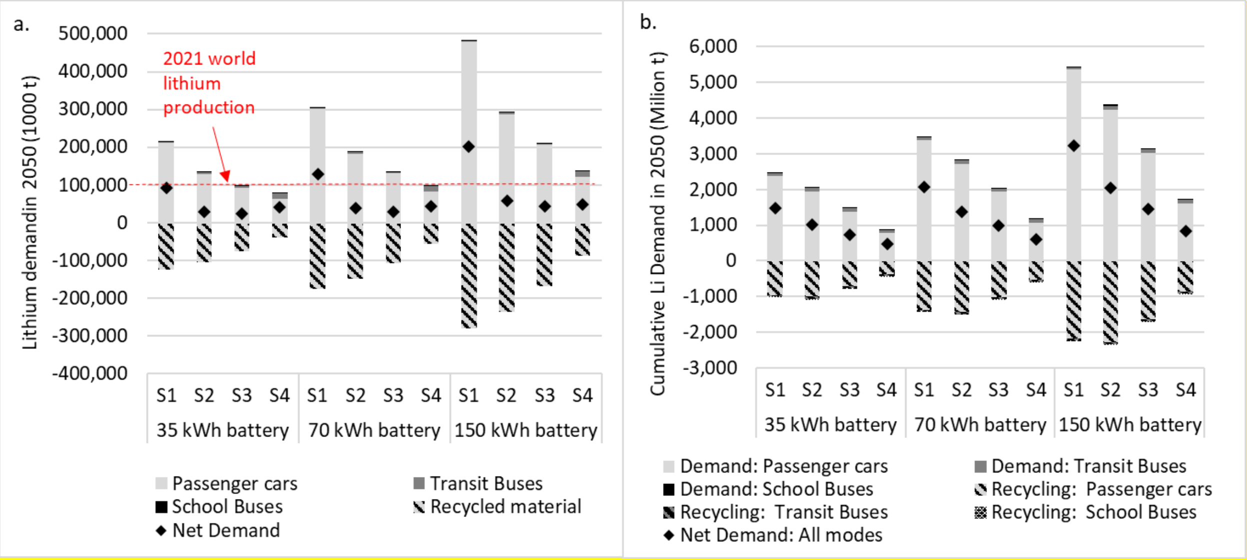
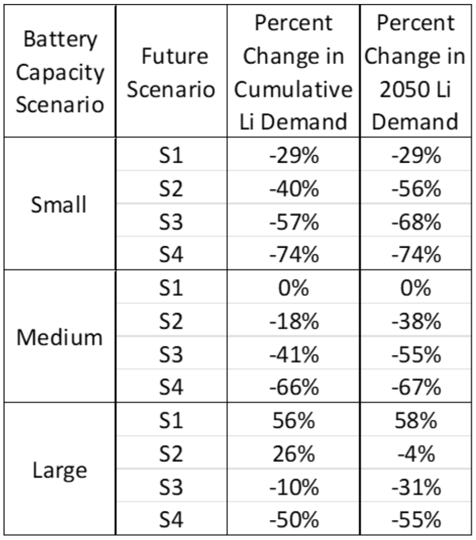
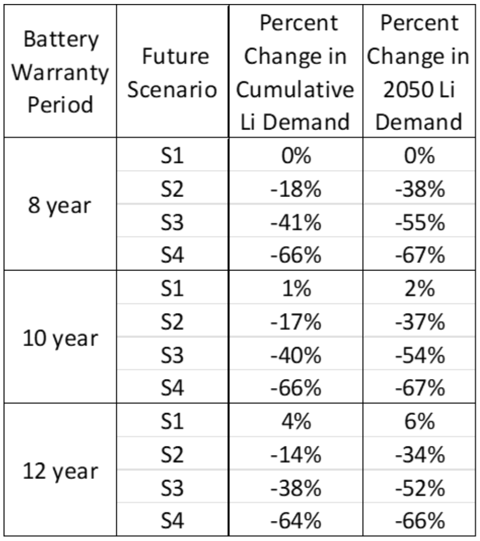


Figure 4. a) US EV battery lithium demand, recycled material potential, and potential net demand in 2050 for scenarios (S1, S2, S3 and S4) with an 8-year battery warranty period in the year 2050. b) US EV Cumulative lithium demand, cumulative recycled material potential, and potential net demand 2010-2050.



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%

Figure 5. Percent change in cumulative Lithium demand as a function of battery size 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%	-38%
	S3	-41%	-55%
	S4	-66%	-67%
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 6. Percent change in Lithium demand as a function of warranty period and decarbonized transportation future

Recycling

Model results show that cumulatively by 2050 38% of new lithium demand can come from recycled LIBs. However, this is under ideal conditions meaning that 98% of lithium is recovered from every LIB retired. This is an unlikely scenario considering current lithium recycling is not widespread. Even under these optimistic assumptions, recycling cannot meet 50 percent of the demand modeled in 2050. Therefore, recycling cannot in the coming decades solve the problem of lithium demand for EV batteries. This is especially true because of the delay of recycled material entering the lithium supply chain due to the 15 year average use phase of an EV. Though recycling will not provide an immediate or sufficient supply of lithium for EV demand, it should be pursued regardless of the decarbonized transportation scenario because at any level of EV deployment, recycling reduces the demand for new lithium extraction.

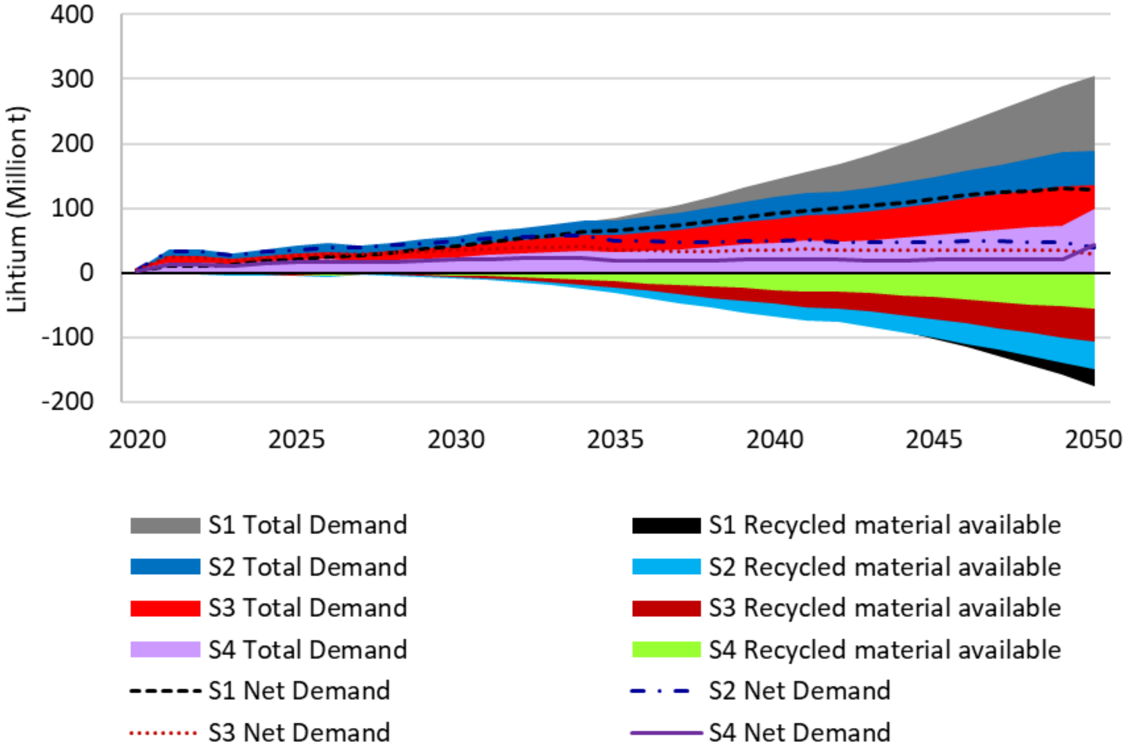


Figure 7. Lithium demand under decarbonized transportation futures assuming medium battery capacity, 8 year warranty period and 98 percent recovery of all lithium from retired batteries in the year in which they retire.

Table 2 shows the cumulative demand for lithium in 2050 required to meet US passenger transportation demand in personal vehicles and buses while reaching a fully decarbonized transportation future. In every scenario except S4, US demand will exceed current global production. Continuing business as usual will result in a demand that is 3 times the current global market. For reference, the US comprised 12% of the global EV market in 2021. If the ideal recycling and recovery is achieved, 27% of lithium demand in 2050 could be met with recovered materials. 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.

Discussion & Recommendations

Reducing US lithium demand requires policy action similar to federal emissions and fuel economy standards for combustion engine vehicles. One of these policies, the Safer Affordable Fuel Efficient (SAFE) Vehicles sets a required average fuel economy for the auto industry. A similar policy for EVs should be created that addresses battery performance standards to ease consumer's range anxiety and reduce lithium demand. A policy of this nature would require batteries to be covered under warranty for up to 12 years and cap rated battery capacity for private passenger vehicles. A battery standard policy is only effective at reducing lithium demand if private car demand stays the same or decreases because unlike combustion vehicles and gasoline, cutting lithium demand is more an issue of vehicle demand rather than a vehicle miles traveled issue. Therefore, in addition to policies for battery standards, incentives for public electric busses should be made available to the transportation industry and its consumers. Investing in public transportation will shift the American cultural norm that requires individuals to own private vehicles thereby reducing the demand of LIBs and lithium. Furthermore, this investment will make transportation more accessible and equitable. LIB recycling also requires investment from the auto industry and government as it is a viable source of lithium for future demand. The investment required for recycling to be considered a reliable source of lithium in the future moves beyond the creation of recycling facilities. A system for tracking batteries from creation to disposal is necessary for regulators to ensure battery recycling is happening at a vehicle's end-of-life. While recycling does not reduce demand for lithium, it can prevent unnecessary new mining that is harmful to people and planet.

Appendix

Table A1. Battery failure calculated from Weibull distribution

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 A2. 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	base case	lite	moderate	ambitious	base case	lite	moderate	ambitious	base case	lite	moderate	ambitious
2020	.71E+06	.68E+06	.06E+06	.02E+06	.32E+06	.29E+06	.66E+06	.63E+06	.51E+06	.48E+06	.86E+06	.82E+06
2021	.02E+06	.42E+07	.72E+07	.69E+06	.07E+07	.33E+07	.37E+07	.29E+07	.59E+07	.13E+07	.64E+07	.92E+07
2022	.84E+06	.43E+07	.71E+07	.60E+06	.05E+07	.35E+07	.37E+07	.28E+07	.58E+07	.17E+07	.65E+07	.92E+07
2023	.93E+06	.03E+07	.45E+07	.77E+06	.35E+07	.76E+07	.98E+07	.16E+07	.05E+07	.21E+07	.02E+07	.71E+07
2024	.32E+07	.38E+07	.72E+07	.07E+07	.77E+07	.21E+07	.32E+07	.39E+07	.65E+07	.85E+07	.50E+07	.01E+07
2025	.57E+07	.68E+07	.92E+07	.19E+07	.13E+07	.61E+07	.59E+07	.54E+07	.22E+07	.44E+07	.91E+07	.24E+07
2026	.87E+07	.98E+07	.12E+07	.31E+07	.55E+07	.02E+07	.87E+07	.70E+07	.89E+07	.06E+07	.33E+07	.47E+07
2027	.02E+07	.87E+07	.08E+07	.17E+07	.83E+07	.02E+07	.90E+07	.60E+07	.43E+07	.28E+07	.52E+07	.45E+07
2028	.36E+07	.17E+07	.29E+07	.29E+07	.32E+07	.44E+07	.19E+07	.76E+07	.19E+07	.92E+07	.98E+07	.70E+07
2029	.74E+07	.49E+07	.51E+07	.41E+07	.86E+07	.88E+07	.50E+07	.93E+07	.05E+07	.61E+07	.46E+07	.95E+07
2030	.17E+07	.82E+07	.74E+07	.54E+07	.46E+07	.33E+07	.83E+07	.11E+07	.00E+07	.31E+07	.96E+07	.22E+07
2031	.75E+07	.25E+07	.07E+07	.77E+07	.25E+07	.89E+07	.25E+07	.38E+07	.20E+07	.11E+07	.56E+07	.58E+07
2032	.24E+07	.63E+07	.33E+07	.92E+07	.95E+07	.40E+07	.60E+07	.58E+07	.31E+07	.89E+07	.10E+07	.88E+07
2033	.77E+07	.01E+07	.59E+07	.07E+07	.69E+07	.93E+07	.96E+07	.78E+07	.05E+08	.07E+08	.66E+07	.19E+07
2034	.36E+07	.44E+07	.88E+07	.23E+07	.54E+07	.51E+07	.36E+07	.00E+07	.18E+08	.16E+08	.28E+07	.52E+07

2035	.84E+07	.48E+07	.95E+07	.15E+07	.29E+07	.72E+07	.55E+07	.98E+07	.31E+08	.21E+08	.71E+07	.61E+07
2036	.52E+07	.92E+07	.26E+07	.31E+07	.25E+07	.35E+07	.99E+07	.21E+07	.46E+08	.31E+08	.40E+07	.97E+07
2037	.25E+07	.37E+07	.57E+07	.48E+07	.03E+08	.97E+07	.43E+07	.44E+07	.63E+08	.41E+08	.01E+08	.32E+07
2038	.04E+07	.83E+07	.89E+07	.65E+07	.14E+08	.61E+07	.88E+07	.67E+07	.81E+08	.51E+08	.08E+08	.68E+07
2039	.99E+07	.39E+07	.31E+07	.92E+07	.27E+08	.04E+08	.43E+07	.01E+07	.01E+08	.62E+08	.16E+08	.15E+07
2040	.85E+07	.89E+07	.66E+07	.11E+07	.40E+08	.10E+08	.91E+07	.27E+07	.21E+08	.72E+08	.23E+08	.55E+07
2041	.08E+08	.40E+07	.01E+07	.30E+07	.53E+08	.17E+08	.40E+07	.53E+07	.41E+08	.83E+08	.31E+08	.94E+07
2042	.16E+08	.55E+07	.18E+07	.29E+07	.65E+08	.21E+08	.70E+07	.59E+07	.62E+08	.91E+08	.37E+08	.15E+07
2043	.26E+08	.03E+07	.50E+07	.45E+07	.80E+08	.28E+08	.17E+07	.82E+07	.86E+08	.01E+08	.44E+08	.52E+07
2044	.38E+08	.55E+07	.87E+07	.65E+07	.96E+08	.35E+08	.69E+07	.09E+07	.12E+08	.13E+08	.52E+08	.94E+07
2045	.49E+08	.01E+08	.28E+07	.87E+07	.13E+08	.43E+08	.02E+08	.40E+07	.37E+08	.25E+08	.61E+08	.39E+07
2046	.62E+08	.08E+08	.77E+07	.18E+07	.30E+08	.52E+08	.09E+08	.78E+07	.64E+08	.38E+08	.70E+08	.93E+07
2047	.73E+08	.14E+08	.19E+07	.41E+07	.47E+08	.60E+08	.15E+08	.09E+07	.91E+08	.50E+08	.79E+08	.40E+07
2048	.86E+08	.20E+08	.62E+07	.64E+07	.65E+08	.68E+08	.21E+08	.40E+07	.19E+08	.63E+08	.88E+08	.88E+07
2049	.99E+08	.26E+08	.06E+07	.88E+07	.83E+08	.77E+08	.27E+08	.73E+07	.49E+08	.77E+08	.98E+08	.04E+08
2050	.11E+08	.29E+08	.30E+07	.25E+07	.01E+08	.82E+08	.31E+08	.19E+07	.79E+08	.88E+08	.06E+08	.20E+08
Cumulative	.39E+09	.93E+09	.39E+09	.76E+08	.39E+09	.70E+09	.94E+09	.06E+09	.36E+09	.23E+09	.03E+09	.62E+09

Table A3. Lithium demand (kg) for US passenger vehicles assuming a 10 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	Scenaro 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
2020	.71E+06	.68E+06	.06E+06	.02E+06	.32E+06	.29E+06	.66E+06	.63E+06	.51E+06	.49E+06	.86E+06	.83E+06
2021	.02E+06	.42E+07	.72E+07	.69E+06	.07E+07	.33E+07	.37E+07	.29E+07	.59E+07	.13E+07	.64E+07	.92E+07
2022	.84E+06	.43E+07	.71E+07	.60E+06	.05E+07	.35E+07	.37E+07	.28E+07	.58E+07	.17E+07	.65E+07	.92E+07
2023	.94E+06	.03E+07	.45E+07	.78E+06	.35E+07	.76E+07	.98E+07	.16E+07	.06E+07	.21E+07	.02E+07	.71E+07
2024	.32E+07	.38E+07	.72E+07	.08E+07	.77E+07	.22E+07	.32E+07	.39E+07	.66E+07	.85E+07	.50E+07	.02E+07
2025	.57E+07	.68E+07	.92E+07	.19E+07	.13E+07	.61E+07	.59E+07	.55E+07	.23E+07	.44E+07	.91E+07	.24E+07
2026	.87E+07	.98E+07	.13E+07	.31E+07	.55E+07	.02E+07	.87E+07	.71E+07	.89E+07	.07E+07	.34E+07	.48E+07
2027	.03E+07	.88E+07	.08E+07	.18E+07	.84E+07	.02E+07	.91E+07	.61E+07	.44E+07	.28E+07	.53E+07	.46E+07
2028	.37E+07	.18E+07	.29E+07	.29E+07	.32E+07	.44E+07	.20E+07	.77E+07	.21E+07	.94E+07	.99E+07	.71E+07
2029	.75E+07	.50E+07	.51E+07	.41E+07	.86E+07	.89E+07	.51E+07	.93E+07	.07E+07	.62E+07	.47E+07	.96E+07
2030	.18E+07	.85E+07	.77E+07	.56E+07	.48E+07	.38E+07	.86E+07	.13E+07	.03E+07	.38E+07	.01E+07	.25E+07
2031	.78E+07	.33E+07	.13E+07	.80E+07	.28E+07	.00E+07	.33E+07	.42E+07	.25E+07	.30E+07	.69E+07	.65E+07
2032	.27E+07	.70E+07	.38E+07	.94E+07	.99E+07	.51E+07	.68E+07	.62E+07	.37E+07	.01E+08	.22E+07	.94E+07
2033	.80E+07	.08E+07	.64E+07	.09E+07	.74E+07	.03E+07	.03E+07	.82E+07	.06E+08	.09E+08	.77E+07	.24E+07
2034	.40E+07	.52E+07	.94E+07	.26E+07	.60E+07	.62E+07	.44E+07	.04E+07	.19E+08	.18E+08	.41E+07	.58E+07
2035	.90E+07	.56E+07	.01E+07	.18E+07	.37E+07	.85E+07	.64E+07	.02E+07	.32E+08	.23E+08	.85E+07	.69E+07
2036	.58E+07	.02E+07	.33E+07	.35E+07	.34E+07	.48E+07	.09E+07	.26E+07	.48E+08	.33E+08	.55E+07	.05E+07
2037	.32E+07	.48E+07	.65E+07	.52E+07	.04E+08	.12E+07	.54E+07	.49E+07	.65E+08	.43E+08	.03E+08	.41E+07
2038	.13E+07	.94E+07	.97E+07	.69E+07	.16E+08	.77E+07	.99E+07	.73E+07	.83E+08	.53E+08	.10E+08	.78E+07
2039	.09E+07	.51E+07	.40E+07	.97E+07	.29E+08	.05E+08	.56E+07	.08E+07	.04E+08	.65E+08	.18E+08	.26E+07
2040	.97E+07	.03E+07	.76E+07	.16E+07	.41E+08	.12E+08	.05E+07	.34E+07	.24E+08	.76E+08	.26E+08	.66E+07
2041	.09E+08	.55E+07	.12E+07	.36E+07	.55E+08	.20E+08	.55E+07	.61E+07	.45E+08	.87E+08	.33E+08	.07E+07

2042	.18E+08	.71E+07	.29E+07	.35E+07	.67E+08	.23E+08	.87E+07	.68E+07	.65E+08	.94E+08	.39E+08	.28E+07
2043	.28E+08	.20E+07	.63E+07	.52E+07	.83E+08	.30E+08	.35E+07	.92E+07	.90E+08	.05E+08	.47E+08	.67E+07
2044	.40E+08	.74E+07	.00E+07	.72E+07	.99E+08	.38E+08	.88E+07	.19E+07	.16E+08	.17E+08	.55E+08	.10E+07
2045	.51E+08	.03E+08	.42E+07	.95E+07	.16E+08	.46E+08	.05E+08	.50E+07	.42E+08	.29E+08	.64E+08	.56E+07
2046	.64E+08	.10E+08	.93E+07	.26E+07	.33E+08	.55E+08	.11E+08	.90E+07	.70E+08	.43E+08	.74E+08	.12E+07
047	.76E+08	.16E+08	.35E+07	.49E+07	.51E+08	.63E+08	.17E+08	.21E+07	.97E+08	.56E+08	.83E+08	.59E+07
2048	.89E+08	.22E+08	.79E+07	.73E+07	.69E+08	.72E+08	.23E+08	.54E+07	.26E+08	.69E+08	.93E+08	.01E+08
2049	.02E+08	.29E+08	.25E+07	.98E+07	.88E+08	.81E+08	.29E+08	.87E+07	.57E+08	.83E+08	.02E+08	.06E+08
2050	.15E+08	.32E+08	.51E+07	.35E+07	.07E+08	.86E+08	.34E+08	.34E+07	.87E+08	.94E+08	.11E+08	.23E+08
Cumulative	.42E+09	.96E+09	.41E+09	.88E+08	.44E+09	.75E+09	.97E+09	.08E+09	.43E+09	.30E+09	.08E+09	.65E+09

Table A4. Lithium demand (kg) for US passenger vehicles assuming a 12 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	.71E+06	.68E+06	.06E+06	.02E+06	.32E+06	.29E+06	.66E+06	.63E+06	.51E+06	.49E+06	.86E+06	.83E+06
2021	.03E+06	.42E+07	.72E+07	.69E+06	.07E+07	.33E+07	.37E+07	.29E+07	.59E+07	.13E+07	.64E+07	.92E+07
2022	.85E+06	.43E+07	.72E+07	.61E+06	.05E+07	.35E+07	.37E+07	.29E+07	.58E+07	.17E+07	.65E+07	.92E+07
2023	.95E+06	.03E+07	.45E+07	.79E+06	.35E+07	.76E+07	.98E+07	.16E+07	.06E+07	.21E+07	.02E+07	.72E+07
2024	.32E+07	.39E+07	.73E+07	.08E+07	.77E+07	.22E+07	.33E+07	.40E+07	.66E+07	.85E+07	.50E+07	.02E+07
2025	.58E+07	.68E+07	.92E+07	.20E+07	.14E+07	.62E+07	.60E+07	.55E+07	.24E+07	.45E+07	.92E+07	.25E+07
2026	.88E+07	.99E+07	.13E+07	.32E+07	.56E+07	.03E+07	.88E+07	.71E+07	.90E+07	.08E+07	.35E+07	.49E+07
2027	.03E+07	.88E+07	.09E+07	.18E+07	.85E+07	.03E+07	.92E+07	.62E+07	.45E+07	.30E+07	.54E+07	.47E+07
2028	.37E+07	.18E+07	.30E+07	.30E+07	.33E+07	.45E+07	.21E+07	.78E+07	.22E+07	.95E+07	.01E+07	.72E+07
2029	.76E+07	.51E+07	.52E+07	.42E+07	.88E+07	.90E+07	.53E+07	.95E+07	.09E+07	.64E+07	.50E+07	.99E+07
2030	.20E+07	.87E+07	.78E+07	.57E+07	.50E+07	.40E+07	.88E+07	.15E+07	.06E+07	.41E+07	.05E+07	.29E+07

2031	.79E+07	.35E+07	.14E+07	.81E+07	.31E+07	.03E+07	.35E+07	.44E+07	.29E+07	.33E+07	.72E+07	.69E+07
2032	.31E+07	.80E+07	.45E+07	.98E+07	.04E+07	.65E+07	.78E+07	.68E+07	.45E+07	.03E+08	.39E+07	.04E+07
2033	.87E+07	.31E+07	.80E+07	.18E+07	.84E+07	.36E+07	.27E+07	.94E+07	.07E+08	.14E+08	.15E+07	.43E+07
2034	.48E+07	.73E+07	.09E+07	.34E+07	.71E+07	.93E+07	.66E+07	.15E+07	.21E+08	.23E+08	.75E+07	.76E+07
2035	.00E+07	.76E+07	.15E+07	.25E+07	.51E+07	.12E+07	.84E+07	.13E+07	.35E+08	.28E+08	.17E+07	.86E+07
2036	.70E+07	.24E+07	.48E+07	.43E+07	.52E+07	.80E+07	.31E+07	.38E+07	.51E+08	.38E+08	.91E+07	.24E+07
2037	.48E+07	.72E+07	.82E+07	.61E+07	.06E+08	.48E+07	.79E+07	.63E+07	.68E+08	.49E+08	.07E+08	.63E+07
2038	.31E+07	.21E+07	.17E+07	.79E+07	.18E+08	.02E+08	.27E+07	.88E+07	.87E+08	.60E+08	.14E+08	.02E+07
2039	.31E+07	.81E+07	.62E+07	.08E+07	.32E+08	.10E+08	.87E+07	.24E+07	.09E+08	.72E+08	.23E+08	.52E+07
2040	.02E+08	.36E+07	.99E+07	.28E+07	.45E+08	.17E+08	.39E+07	.52E+07	.29E+08	.83E+08	.31E+08	.94E+07
2041	.12E+08	.91E+07	.38E+07	.49E+07	.59E+08	.25E+08	.92E+07	.80E+07	.51E+08	.95E+08	.39E+08	.38E+07
2042	.21E+08	.10E+07	.57E+07	.50E+07	.72E+08	.29E+08	.27E+07	.89E+07	.73E+08	.03E+08	.46E+08	.62E+07
2043	.32E+08	.63E+07	.93E+07	.67E+07	.88E+08	.36E+08	.79E+07	.14E+07	.99E+08	.15E+08	.54E+08	.03E+07
2044	.44E+08	.02E+08	.33E+07	.89E+07	.06E+08	.44E+08	.04E+08	.44E+07	.27E+08	.28E+08	.63E+08	.49E+07
2045	.57E+08	.08E+08	.78E+07	.13E+07	.23E+08	.53E+08	.10E+08	.77E+07	.54E+08	.41E+08	.72E+08	.98E+07
2046	.70E+08	.15E+08	.31E+07	.46E+07	.42E+08	.62E+08	.17E+08	.18E+07	.83E+08	.55E+08	.83E+08	.57E+07
2047	.83E+08	.22E+08	.77E+07	.71E+07	.60E+08	.71E+08	.23E+08	.52E+07	.12E+08	.69E+08	.93E+08	.01E+08
2048	.96E+08	.28E+08	.24E+07	.96E+07	.79E+08	.81E+08	.30E+08	.87E+07	.43E+08	.83E+08	.03E+08	.06E+08
2049	.10E+08	.35E+08	.73E+07	.23E+07	.00E+08	.90E+08	.36E+08	.23E+07	.75E+08	.98E+08	.13E+08	.12E+08
2050	.24E+08	.39E+08	.00E+08	.61E+07	.19E+08	.97E+08	.41E+08	.72E+07	.07E+08	.10E+08	.22E+08	.29E+08
Cumlative	.49E+09	.04E+09	.46E+09	.16E+08	.54E+09	.86E+09	.05E+09	.12E+09	.59E+09	.47E+09	.20E+09	.71E+09

Recycled Material and Circularity Potential

Table A5. 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	Decycled material available	Net demand	Demand	Recycled material available	Net demand	Demand	Recycled material available	Net demand	Demand	Recycled material available	Net demand
2020	.6E+06	.3E+06	.3E+06	.6E+06	.3E+06	.3E+06	.3E+06	.7E+06	.7E+06	.3E+06	.7E+06	.6E+06
2021	.2E+07	.5E+06	.1E+07	.6E+07	.8E+06	.3E+07	.2E+07	.0E+06	.0E+07	.8E+07	.9E+06	.6E+07
2022	.2E+07	.6E+06	.1E+07	.7E+07	.3E+06	.4E+07	.0E+07	.3E+06	.7E+07	.2E+07	.2E+06	.0E+07
2023	.5E+07	.8E+06	.3E+07	.1E+07	.8E+06	.7E+07	.2E+07	.6E+06	.9E+07	.4E+07	.4E+06	.1E+07
2024	.0E+07	.1E+06	.8E+07	.7E+07	.5E+06	.2E+07	.7E+07	.0E+06	.4E+07	.7E+07	.8E+06	.5E+07
2025	.4E+07	.6E+06	.2E+07	.1E+07	.3E+06	.6E+07	.0E+07	.6E+06	.6E+07	.9E+07	.2E+06	.6E+07
2026	.9E+07	.0E+06	.6E+07	.6E+07	.3E+06	.0E+07	.3E+07	.2E+06	.9E+07	.1E+07	.6E+06	.8E+07
2027	.0E+07	.0E+06	.8E+07	.3E+07	.4E+06	.9E+07	.1E+07	.6E+06	.8E+07	.8E+07	.6E+06	.6E+07
2028	.5E+07	.8E+06	.2E+07	.7E+07	.5E+06	.3E+07	.4E+07	.4E+06	.1E+07	.0E+07	.1E+06	.7E+07
2029	.0E+07	.8E+06	.7E+07	.2E+07	.9E+06	.6E+07	.7E+07	.5E+06	.3E+07	.1E+07	.8E+06	.9E+07
2030	.7E+07	.5E+06	.1E+07	.7E+07	.7E+06	.9E+07	.1E+07	.9E+06	.5E+07	.4E+07	.6E+06	.0E+07
2031	.6E+07	.0E+06	.8E+07	.4E+07	.1E+07	.3E+07	.6E+07	.6E+06	.8E+07	.7E+07	.6E+06	.2E+07
2032	.3E+07	.9E+06	.3E+07	.9E+07	.4E+07	.5E+07	.0E+07	.1E+07	.9E+07	.0E+07	.9E+06	.3E+07
2033	.0E+07	.3E+07	.8E+07	.5E+07	.9E+07	.6E+07	.4E+07	.4E+07	.0E+07	.2E+07	.7E+06	.3E+07
2034	.9E+07	.6E+07	.3E+07	.2E+07	.5E+07	.7E+07	.8E+07	.8E+07	.0E+07	.5E+07	.1E+07	.4E+07
2035	.5E+07	.0E+07	.5E+07	.1E+07	.1E+07	.9E+07	.8E+07	.3E+07	.5E+07	.2E+07	.3E+07	.9E+07
2036	.5E+07	.5E+07	.0E+07	.7E+07	.9E+07	.8E+07	.3E+07	.8E+07	.5E+07	.5E+07	.6E+07	.9E+07
2037	.1E+08	.1E+07	.4E+07	.4E+07	.6E+07	.7E+07	.7E+07	.3E+07	.4E+07	.7E+07	.9E+07	.9E+07
2038	.2E+08	.8E+07	.9E+07	.0E+08	.4E+07	.7E+07	.2E+07	.8E+07	.4E+07	.0E+07	.1E+07	.8E+07
2039	.3E+08	.4E+07	.6E+07	.1E+08	.0E+07	.9E+07	.9E+07	.3E+07	.6E+07	.4E+07	.4E+07	.1E+07
2040	.4E+08	.2E+07	.2E+07	.2E+08	.7E+07	.0E+07	.4E+07	.8E+07	.6E+07	.7E+07	.6E+07	.1E+07
2041	.6E+08	.0E+07	.6E+07	.2E+08	.4E+07	.1E+07	.9E+07	.3E+07	.6E+07	.0E+07	.9E+07	.1E+07
2042	.7E+08	.9E+07	.9E+07	.2E+08	.7E+07	.8E+07	.1E+07	.5E+07	.6E+07	.9E+07	.9E+07	.0E+07

2043	.8E+08	.0E+07	.0E+08	.3E+08	.4E+07	.8E+07	.5E+07	.0E+07	.5E+07	.1E+07	.2E+07	.0E+07
2044	.0E+08	.0E+07	.1E+08	.4E+08	.2E+07	.8E+07	.0E+08	.6E+07	.5E+07	.4E+07	.4E+07	.0E+07
2045	.2E+08	.0E+08	.1E+08	.5E+08	.0E+08	.8E+07	.1E+08	.2E+07	.5E+07	.8E+07	.7E+07	.0E+07
2046	.3E+08	.1E+08	.2E+08	.6E+08	.1E+08	.9E+07	.1E+08	.9E+07	.6E+07	.3E+07	.2E+07	.1E+07
2047	.5E+08	.3E+08	.2E+08	.7E+08	.2E+08	.9E+07	.2E+08	.5E+07	.6E+07	.6E+07	.5E+07	.1E+07
2048	.7E+08	.4E+08	.3E+08	.8E+08	.3E+08	.8E+07	.3E+08	.2E+07	.5E+07	.0E+07	.9E+07	.1E+07
2049	.9E+08	.6E+08	.3E+08	.9E+08	.4E+08	.8E+07	.3E+08	.9E+07	.5E+07	.4E+07	.2E+07	.1E+07
2050	.1E+08	.3E+07	.2E+08	.9E+08	.6E+07	.1E+08	.4E+08	.5E+07	.2E+07	.0E+08	.9E+07	.0E+07
Cum-lative	.5E+09	.3E+09	.2E+09	.9E+09	.4E+09	.4E+09	.1E+09	.0E+09	.0E+09	.2E+09	.6E+08	.3E+08

Table A6. 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+0
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
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

Table A7. Cumulative lithium circularity potential in 2050 assuming medium battery scenario and 8 year warranty period

Scenario 1	Scenario 2	Scenario 3	Scenario 4
38%	49%	49%	47%

Table A8. . 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
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 A9. US EV passenger car stock, sales, and retirements for Scenarios 3 and 4.

	Scenario 3			Scenario 4		
	EV Stock	EVs Sold	EVs retired	EV Stock	EVs Sold	EVs retired
Year	3774	3774	24	3774	3774	24
2010	13524	9750	86	13524	9750	86
2011	28174	14650	179	28174	14650	179
2012	75864	47690	498	75864	47690	498

2013	139284	63420	958	139284	63420	958
2014	210328	71044	1525	210328	71044	1525
2015	297059	86731	2388	297059	86731	2388
2016	401546	104487	3645	401546	104487	3645
2017	640369	238823	6027	640369	238823	6027
2018	882281	241912	8830	882281	241912	8830
2019	1138654	231088	12003	1138654	231088	12003
2020	3588676	2462025	30328	2350164	1223512	22452
2021	6038698	2480351	49858	3561674	1233961	34054
2022	8002505	2013664	67346	4597462	1069842	45539
2023	10210648	2275489	96640	5755676	1203753	63063
2024	12663126	2549119	139420	7036316	1343703	87394
2025	15359940	2836234	190333	8439382	1490461	116424
2026	18301090	3131483	256321	9964874	1641917	153065
2027	21486576	3441807	334000	11612793	1800984	195751
2028	24916398	3763821	424431	13383138	1966096	244910
2029	28590556	4098588	529850	15275908	2137681	302400
2030	32509049	4448343	653033	17291105	2317597	369435
2031	36671878	4815862	787290	19428728	2507058	441982
2032	41079043	5194456	963138	21688778	2702031	533220
2033	45730544	5614639	1184312	24071253	2915695	644729
2034	50626381	6080148	1416725	26576154	3149631	762036
2035	55766554	6556897	1649959	29203482	3389364	880809
2036	61151062	7034467	1889660	31953236	3630563	1003375
2037	66779906	7518504	2139585	34825415	3875555	1131312
2038	72653086	8012765	2400025	37820021	4125918	1264723
2039	78770602	8517541	2671983	40937053	4381755	1404175
2040	85132454	9033834	2956604	44176512	4643634	1550100
2041	91738642	9562791	3253912	47538396	4911984	1702439
2042	98589165	10104435	3566428	51022706	5186750	1862792
2043	105684024	10661288	3893192	54629443	5469529	2030206
2044	113023219	11232387	4233544	58358606	5759369	2204278
2045	120606750	11817075	4588281	62210195	6055866	2385516
2046	128434617	12416148	4960223	66184210	6359531	2575320
2047	136506820	13032426	5354538	70280651	6671761	2777788

2048	144823358	13671076	5757673	74499518	6996655	2983463
2049	153459847	14394162	6174782	78873382	7357327	3194901
2050	153459847	14394162	6174782	78873382	7357327	3194901

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