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Lithium-Ion Batteries: Can we meet the demand sustainably?

Last edit July 10, 2022 1 PM

For whom this essay is intended: those wishing to understand the supply chain, resource and environmental issues involved in meeting the surging demand for Li-ion batteries.

Guide to contents

Summary

If society is to deal with climate change, then two essential goals are the electrification of transportation and the widespread deployment of electrical energy storage for the intermittent production of electricity from wind and solar facilities. This almost certainly implies a greatly increased demand for lithium-ion batteries We describe the various issues involved in obtaining the materials necessary for the production of these batteries, of which cobalt and lithium are, for the next several years, the most critical, though nickel is likely to rise in importance. These issues involve the current and near-term production rates, the domestic and global reserves of these materials and the environmental and societal impacts associated with their production. There are ample reserves of these materials, but the rate at which they are produced and refined must be increased many fold if they are to meet the expected increase in demand. We discuss the dominance by various countries in controlling the current production of lithium and cobalt as well as the impact of their extraction. We discuss the role that recycling can play in mitigating supply chain issues and thus the adverse impacts of mining. We also consider the evolution of various material components of the batteries including the possible substitution of sodium or magnesium for lithium.

Why the need for batteries?

By now, if there are those who still doubt the reality of human-driven climate change, and the urgent necessity for California, the United States, and the rest of the world to drastically cut their use of fossil fuels, no further presentation of evidence is likely to make any impression. We therefore take it as given, that we must rapidly replace fossil fuels with non-CO_2-emitting sources of energy, including nuclear, wind, solar and others.

Electrification is the key to doing this and the intermittent sources—wind and solar—play, and will continue play, a dominant role. As outlined in a previous essay,[1] to significantly increase the amount of wind, and especially solar, energy here in California, it will be essential to increase the ability to store large quantities of energy and this will almost certainly demand grid-scale lithium-ion batteries.

More importantly, on a national and global scale, it will be essential to electrify the transportation sector. That is, it is critical that we increase the availability and use of electric vehicles (EVs). This will, in turn, dramatically increase the demand for lithium-ion batteries.

In this essay, therefore, we explore the question of whether there are, and will continue to be, adequate supplies of the critical materials necessary to meet current and projected demands.

[1] http://www.centralcoastclimatescience.org/uploads/5/3/8/1/53812733/duckcurve_essay.pdf

How lithium-ion batteries work

Before taking up these issues, however it is useful to have a basic understanding of how lithium-ion batteries work and the role of the critical components in their operation.

First of all, what does the "ion" mean in lithium-ion batteries? An ion is simply an atom which has lost one or more of its negatively charged electrons, and therefore has a positive electrical charge.

An instructive illustration of how a Li-ion battery works is seen in Figure 1[2].

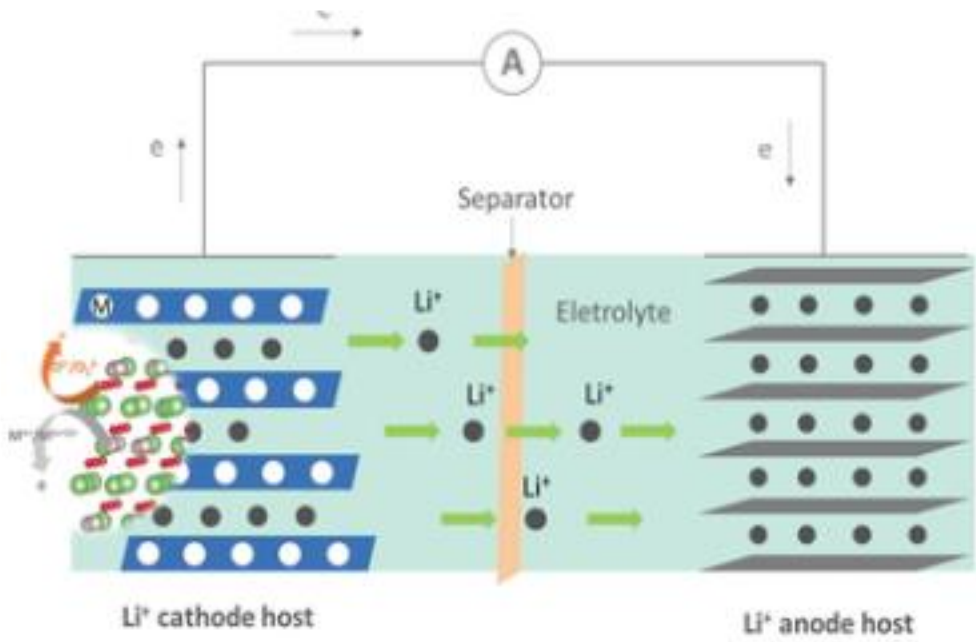

Figure 1. The diagram shows a Li-Ion battery during the charging phase. The A in the circle on top represents an external voltage source which moves electrons through the wire from the cathode on the left to the anode on the right. In response, the positively charged Li ions move through the conducting fluid (in green), called the electrolyte, where the ions are stored at the anode.

In all batteries, positively charged ions move back and forth through the battery cell, while electrons flow in the external circuit, carrying an identical quantity of negative charge. During the *discharge* phase of the cycle, electrons flow from the negative electrode (anode) towards the positive electrode (cathode) through the external circuit. Thus, during its active use, energy is transferred from the battery to the external circuit, where work can be done, like powering an appliance. During the *recharging* process an

[2] There are also many animated illustrations: Here is an interesting one, though a thinly disguised advertisement for Tesla: https://www.youtube.com/watch?v=VxMM4g2Sk8U and you will have to skip an ad.

external source of voltage causes the direction of current flow to be reversed, as illustrated in Fig. 1.

The anode, the negative side of the battery, is commonly made of some form of graphite[3], which is an abundant substance. The cathode can be made of a variety of compounds, including oxides of lithium and cobalt and other metals including nickel, cadmium, manganese and copper. Currently, cobalt and other elements, especially nickel, are essential to Li-ion batteries used in most applications. The electrolyte filling the battery is typically non-aqueous because lithium reacts violently with water. Also, the battery is in a sealed container that keeps moisture away from its contents.

The two most critical materials: lithium and cobalt

While the alternatives to the lithium cobalt-oxide batteries described below may eventually become widespread, for the next several years the increasing demand for batteries for electric vehicles is very likely going to be met by these designs. The issues which must be addressed are the quantity of these materials available, their production capacity, supply chain issues and societal and environmental damage. Of the other materials, nickel is the next most problematic case as its price has spiked recently and there are supply chain issues. But for the remainder of this essay, we will focus on lithium and cobalt.

<u>Some definition of terms:</u> "Reserves", "Resources", "Production Rates"

There are several more precise levels attached to the rather nebulous phrase "the amount of material available" which have been adopted by the U.S. Geological Survey[4]. They are listed in order of increasing specificity.

<u>Resource:</u> A concentration of naturally occurring …material...in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.
<u>Identified Resource:</u> Resource for which location, grade, quality, and quantity are known or estimated from specific geologic evidence.
<u>Reserves:</u> That part of the reserve base that could be economically extracted or produced at the time of determination. The term "reserves" need not signify that extraction facilities are in place and operative.
<u>Production rate</u>**:** As noted above, the definition of reserves is not the same as what is actually being produced. For the near-term requirements needed for Li-ion batteries, the *amount being produced on an annual basis*—the current <u>production rate</u>—is the most relevant.

[3] See here for a supplier's description of various forms of graphite: https://www.targray.com/li-ion-battery/anode-materials
[4] https://pubs.usgs.gov/unnumbered/7000088/sta13.pdf

We obtain the actual data for lithium and cobalt from the U.S.G.S. Mineral Commodities Summary for 2022[5]. In the data for both lithium and cobalt one finds the heading “World Resources”--the text references this to mean “identified resources” defined above.

Lithium

Reserves, resources, production rates

We begin with estimates of the production rates, reserves and “world resources” for lithium. Most of the estimates in this section are in the metric unit **tonne**, 1000 kg, approximately 2205 pounds. Estimates for these quantities found online vary widely and may refer to “resources” rather than reserves. In our opinion, the most reliable estimates are from the USGS, but these estimates change from year to year.

Here are the USGS data:

Production rates: For 2019, the leading countries are given, with Australia (45,000), Chile (19,300), China (10,800) and Argentina (6,300) being the 4 leading ones. However, this excludes data for the U.S. for proprietary reasons. Excluding the U.S., the world total production rate was 86,000 tonnes. See also a report from the McKinsey consulting firm[6].

Reserves, in millions of metric tonnes: The leading countries are Chile 9.2, Australia 4.7, Argentina 1.9, China 1.5 and the U.S. 0.75. The remaining countries bring the global total to 21.0.

Resources: Owing to continuing exploration, *identified* lithium resources (referred to in the USGS source as “World Resources”) have increased substantially and total about 86 million tons. Lithium resources in the United States are 7.9 million tons. Lithium resources in other countries are: Bolivia, 21 million tons; Argentina, 19.3 million tons; Chile, 9.6 million tons; Australia, 6.4 million tons; China, 5.1 million tons.

Thus, Argentina, Chile and Bolivia, the “lithium salt flat triangle countries”, account for more than 70% of the world’s lithium reserves, which lie beneath their salt flats.

However, for reserves and production rates, Australia is currently an important player along with China. China’s role in lithium production has resulted in significant supply chain issues.

Demand Estimates

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[5] https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf

[6] https://www.mckinsey.com/industries/metals-and-mining/our-insights/lithium-mining-how-new-production-technologies-could-fuel-the-global-ev-revolution. Note that this estimate refers to lithium carbonate, not lithium itself. To go from the carbonate estimate to lithium itself, divide by 5.32. This yields a 2021 production of lithium of about 100,000 tonnes. Note: You may need to accept cookies to access this report.

At the current rate of production, the global reserves would last for about 250 years. But the yearly demand is expected to grow sharply. Demand for lithium on multi-year time scales will depend largely on the demand for lithium in Li-ion batteries which in turn reflects primarily the growth in the electric vehicle market and to a somewhat lesser extent on the use of Li-ion batteries in energy storage. In the report by the McKinsey consulting group cited in footnote 6, the demand up through 2030 was projected to increase at an annual rate of about 25 percent, implying a factor of over 7 in annual demand by 2030 compared to 2021.

Longer term estimates are strongly dependent on the political decisions which the world's nations make regarding the reductions in fossil fuel use. The results are very different for policies *presently in place* and *those necessary to meet the goals of the Paris Agreement*, for example. The International Energy Agency's projection for the next 20 years[7] consequently differs between an increase by a factor of 13 and about 40, depending upon which of these two policy scenarios is adopted; the latter implies an annual growth rate in demand over this 20 year period of about 21 percent.

In any case, to meet the demand even over the next decade requires a *very large expansion of production facilities, with a corresponding need for a very large investment.*

However, in spite of the approximately 7.5-fold increase in demand forecast by McKinsey for 2030 there would still be ample lithium reserves. The total amount which would be consumed is about 3.3 million tonnes, substantially less than the current estimates of reserves.

Even on the 20 year timescale discussed by the IEA and with growth by a factor 40 by 2040, the total lithium consumed, assuming a value of 100,000 tonnes for 2021, is about 22 million tonnes. This is only slightly in excess of the USGS estimate of 21,000,000 tonnes in reserves. In any case, as discussed below however, by 2040 there is a reasonable expectation that recycling of lithium may drastically reduce the *net* annual lithium consumption.

Lithium extraction methods: brine versus ore

There are two distinct sources of lithium. Some is found in ores and must be mined and refined by the usual mining processes. The other source is from lithium-rich brine found extensively in the salt flats in the deserts of Chile, Argentina and Bolivia. In addition, some may be extracted from geothermal reservoirs, like those associated with geothermal energy sources.

More efficient extraction methods are also being developed, effectively increasing the reserve estimates.

Societal and environmental impacts of lithium extraction

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[7] https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf

Because of these two quite different sources of lithium and their locations, the impacts of lithium extraction depend on which of these two sources are involved.
In the case of the extraction of lithium from the salt flats of Chile, for example, there have been concerns raised by the indigenous populations in these areas that the extraction process from these salt flats may deplete or contaminate the precious fresh water supply. However, investigation of this concern[8] did not result in any convincing evidence that this is occurring, but this possibility should be continuously monitored. The amount of water extraction associated with the lithium was estimated to be only 5-10% of the total, with copper mining and tourism being the dominate consumers of water.

For mining, the impacts are similar to those with other mining operations, especially when mines are opened up in new areas devoted to other activities, like farming and grazing. A recent example of this is occurring in Gaston County in North Carolina[9]. The following are comments are taken from the article in footnote 9:

It is argued mines of the proposed size would cause light, noise and dust pollution, as well as contaminate the water supply with poisonous runoff materials. Many of the houses surrounding the site of the proposed mine are not connected to a municipal water system, and instead extract their drinking water from wells, compounding worries that any accidental runoff or contamination of groundwater from the mine would poison their water sources. Farms in the area name the potential pollution of their water sources as a top concern.

Cobalt

We discuss the issues associated with cobalt in a similar to that for lithium, with the January 2022 USGS report being the source for reserve estimates, as it was for lithium.

Reserves, resources, production rates

Production rates:
The Democratic Republic of Congo (DRC) continued to be the world's leading source of mined cobalt, producing 98,000 tonnes in 2020, about 70% of the world's production of 142,000 tonnes.

China was the world's leading producer of refined cobalt, most of which was produced from partially refined cobalt imported from the DRC. China was also the world's leading consumer of cobalt, with more than 80% of its consumption being used by China for the rechargeable battery industry.

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[8] https://www.volkswagenag.com/en/news/stories/2020/03/fact-finding-expedition-to-the-lithium-desert-of-chile.html
[9] https://insideclimatenews.org/news/31052022/powering-electric-cars-the-race-to-mine-lithium-in-americas-backyard/?utm_source=InsideClimate+News&utm_campaign=a9c459d811-&utm_medium=email&utm_term=0_29c928ffb5-a9c459d811-329600157

As discussed below, the major cobalt mines in the DRC are in fact owned by China and this has led to supply chain concerns.

Reserves
The DRC also is the leading country in terms of reserves with 3.5 million tonnes. Australia is 2nd at 1.4 million, with the world's total being 7.6 million.

Resources
Identified world terrestrial cobalt resources are about 25 million tons. The vast majority of these resources are copper deposits in the DRC and neighboring Zambia. There are potentially even larger amounts on the ocean floor, but the environmental and economic implications of development of these sources have not been adequately investigated.

Demand Estimates
In addition to the cobalt used in the cobalt-lithium-metal oxides of Li-ion batteries, there is also significant use of cobalt in the very high temperature resistant alloys used mainly in jet engines. However, the increase in demand for cobalt is mainly driven, as in the case of lithium, by the anticipated utilization of Li-ion batteries.

Cobalt is currently expensive and will likely remain so as the demand is expected to increase by about 35% between 2020 and 2025, driven by its use in EVs[10]. The cumulative consumption up to 2025 is projected to be roughly 1,000,000 tonnes, well below the estimated reserves of 7.6 million tonnes. Extrapolation beyond that is of doubtful significance because there is substantial research devoted to using less, or even no, cobalt in Li-ion batteries, as discussed below. Over the next few years therefore, the issue is not 'running out of cobalt' but the ability to ramp up the production rate from the known reserves.

Societal and environmental impacts of cobalt extraction
Since the DRC is where most of the cobalt mining occurs, we focus on the impacts there. There are two categories of cobalt mines in the DRC. Some of the cobalt comes from the so-called "artisanal" mines which are small operations, sometimes involving even just individuals or individual families.

Many of the mineral rights to rich deposits have been sold by corrupt government officials to Chinse mining companies, so that the Chinese now control the extraction and refining of the majority of the world's cobalt. Given the current crucial role of cobalt in the manufacture of Li-ion batteries, this is a cause for concern.

Many of the workers in this poverty-stricken country who worked in the artisanal mines have migrated to the large-scale Chinese-owned and operated mines, but in both cases there is well-documented evidence of the serious health and societal impacts of cobalt mining on the workers. The rate of birth defects among children whose parents work in or

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[10] https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/global-cobalt-supply-deficit-not-as-dire-analysts-say-66734094. See also: https://blog.energybrainpool.com/en/is-there-enough-cobalt-to-meet-the-need-for-batteries/

around the mines is disturbingly high. A 2021 article in the New Yorker magazine documents these effects in detail[11]. This is corroborated here[12] as well as discussing the need to better evaluate the societal costs of switching to a green energy economy.

Some of the largest users of Li-ion, including Tesla and Apple, were sued on behalf of the child workers associated with cobalt mines because of appalling working conditions, but the case was dismissed on technical grounds. Nevertheless, in response to public pressure over the impacts on the artisanal cobalt mine workers, some major corporations, including Tesla (but not Apple) formed the Fair Cobalt Alliance[13] whose purpose is "to help strengthen and professionalize the DRC's artisanal cobalt minor sector and contribute to local economic development at large."

Of course, this effort does not address the major cobalt mines owned and operated by the Chinese, though they state that they are also working to improve conditions.

In a recent Editorial in SCIENCE magazine[14] Prof. James Turner of the Department of Environmental Studies at Wellesley University, calls attention, as have others, to the urgent need to expand production facilities by at least a factor of 6 for the critical materials used in Li-Ion batteries. But he also points out that "nickel, cobalt and copper and many other relevant materials occur in low-grade ores" which means that enormous amounts of *raw* ore must be mined to get the necessary amount of the expected demand for these minerals. This implies that the potential environmental and societal impacts of this mining are likely to be much more severe than might be supposed based only upon the actual weight of the critical materials themselves, unless some steps are used to control this damage. This points up the urgency of both reducing the amount of cobalt required, as well as establishing large scale recycling, which we discuss below.

In the meantime, Prof. Turner suggests that "third party certification" programs should become common in these mining operations so that there is some accountability of the mining companies. He cites as an example of such a mining certification program the "Initiative for Responsible Mining Assurance"[15]. Such certifications have been used in logging operations.

Batteries with low or no cobalt

The lack of significant domestic supplies of cobalt, the dominance of China in controlling much of the supply, the volatile political situation in the DRC, and finally the environmental and societal aspects of cobalt mining all raise the question of whether reduced, or even no, cobalt in lithium ion batteries is in the offing.

The oxides of lithium and cobalt currently used help to stabilize the reactivity of lithium and significantly reduce the danger of fire. Thus, oxides of lithium and cobalt are an

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[11] https://www.newyorker.com/magazine/2021/05/31/the-dark-side-of-congos-cobalt-rush
[12] https://news.northwestern.edu/stories/2021/12/understanding-cobalts-human-cost/
[13] https://www.faircobaltalliance.org/about-us/about-us/
[14] https://www.science.org/doi/epdf/10.1126/science.add5094
[15] https://responsiblemining.net/

important safety element. But some reduction in the amount of cobalt used may be achieved by increasing the amount of nickel.

In fact, Tesla has been making some use of cobalt-free lithium-iron-phosphate (LFP) batteries for some applications, including in some of its electric vehicles[16].
While these lithium-iron-phosphate batteries[17] are finding use in some vehicles, they are especially appropriate for utility scale battery storage. This is because for a given amount of stored energy there is more weight than in the lithium-cobalt-oxide batteries, but for grid scale storage where total weight and volume are not critical, they offer two significant advantages: they are very safe and stable, and can be recycled many times.

While we have not discussed cost projections for Li-ion batteries, a report produced by the Pacific Northwest National labs gives costs projections for the next decade, along with performance characteristics, for both the lithium-ion nickel manganese cobalt (NMC) and lithium-ion phosphate (LFP) batteries[18].

Prospects for recycling and recovery of material in Li-Ion batteries

The supply chain issues and environmental and societal impacts which we have discussed for the two most critical components of lithium-ion batteries raise the issue of whether recycling of these materials can significantly reduce the need for extraction of lithium and cobalt. For example, a recent comprehensive analysis by Neumann et al., 2022[19] outlines how development of new technologies will impact resource requirements, the nature and extent of material recycling and other factors. They note that recycling is economically justified only when, and thus if, batteries contain significant amounts of metals such as Ni and Co. The regulatory frameworks for recycling differ in scope and effectiveness in the EU, the US and in China. In the US, for example, there is no national regulation of new battery types, although four states regulate the collection and recycling of Li-ion batteries. The diversity of battery cell chemistries makes recycling difficult.

Building plants that can treat a variety of cell types would require significant capital outlays, and in the absence of regulation such an investment is risky. Current recycling processes begin with discharging and dismantling of battery modules. This is followed by crushing, so that the valuable metals in the cathode and anode are concentrated in a "black mass".

Further processing can take place by hydrometallurgy or pyrometallurgy. The former constitutes dissolution of the metallic components, followed by steps to separate the metals. This can lead to recovery rates of over 99% of Ni, Co and Mn, and work well even on mixed-waste streams. In the pyrometallurical approach a high-temperature

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[16] https://electrek.co/2022/04/22/tesla-using-cobalt-free-lfp-batteries-in-half-new-cars-produced/
[17] https://en.wikipedia.org/wiki/Lithium_iron_phosphate_battery ; see also here for Tesla's use for utility-scale storage: https://www.utilitydive.com/news/tesla-shifts-battery-chemistry-for-utility-scale-storage-megawall/600315/
[18] https://www.pnnl.gov/sites/default/files/media/file/Final - ESGC Cost Performance Report 12-11-2020.pdf
[19] https://onlinelibrary.wiley.com/doi/full/10.1002/aenm.202102917

furnace is used to render the metal oxides as an alloy through smelting and roasting. A desirable "design for recycling" approach is described. However, it will be challenging to use such an approach in the US, in the absence of a regulatory framework.

The impact of changing chemical composition on the prospects for substantial recovery of critical minerals by recycling was also discussed in a detailed analysis by Dunn et al. of the Energy and Efficiency Department at UC Davis[20]. They considered six different scenarios for the evolution of the cathode material mix. They also included four different scenarios for the demand for these materials, which in turn depends upon EV sales. The evolution of the amounts of materials used in these batteries may change as, for example, customers demand longer driving distances in a single charge. And finally, these various factors were examined in each of four different regions: China, the EU, and U.S. and the "rest of the world". This means there were 96 different combinations of these scenarios to consider.

Before attempting to summarize their results however, it is important to distinguish two measures of "efficiency": First, the actual extraction efficiency when a battery is recycled, for which the authors assumed a value of 95%. In the paper by Neumann (footnote 19)for example, recovery rates as high as 98-99% are suggested for lithium, manganese, cobalt and nickel. Second, the difference between the *demand* for material and the *actual amount returned from recycling* of batteries at the end of their life.

The latter is the most relevant measure in assessing the role of recycling in the criticality of supply chain for these materials. This will be a function of time when all three factors in the 96 scenarios are taken into account—the history of EV sales, the evolving chemistry of the cathode materials and recycling policy, all of which vary across the four regions considered. In some cases, a point may be reached where 100% "circularity" of cobalt is achieved, depending upon the cathode chemistry adopted. In most cases for lithium, however, the recovery rate is never above about 60% of the demand, so lithium extraction would have to continue.

Regarding policy, part of the concluding paragraph of their paper is worth quoting:

The US trails behind with no national policy that requires or incentivizes material circularity, although there have been major efforts to decrease the cost of recycling, specifically through the development of direct recycling by the ReCell center. Despite the lack of effective policy in much of the world, a substantial number of batteries will be reaching their end of life in the next 20 years, which coincides with the large increase in material demand and presents an opportunity for effective recovery. Thus, there is still sufficient time to enact policy to achieve greater LIB material circularity and realize the potential economic and environmental benefits of creating a domestic supply of secondary materials in high-demand countries and regions.

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[20] https://pubs.acs.org/doi/full/10.1021/acs.est.0c07030 Note: the full text is behind a paywall; only the abstract is available without a subscription

As remarked above, an obstacle to efficient recycling is the difference in packaging and chemistries between battery packs. However, if a company like Tesla receives batteries from a small number of suppliers or, as they are now doing, manufacture their own, then it is reasonable to expect a higher recovery rate. In a recent report [21] Tesla is said to have established their own recycling facility and to have achieved a recovery fraction of 92%.

Alternative chemistries for Li-ion batteries; Why lithium?
Even though there are adequate reserves of lithium, since supply chain issues and China's dominance of lithium supply is currently a domestic concern, an obvious question to ask is: what is so special about lithium? Perhaps you remember the 'periodic table' when you took a chemistry course in high school. It looks like this:

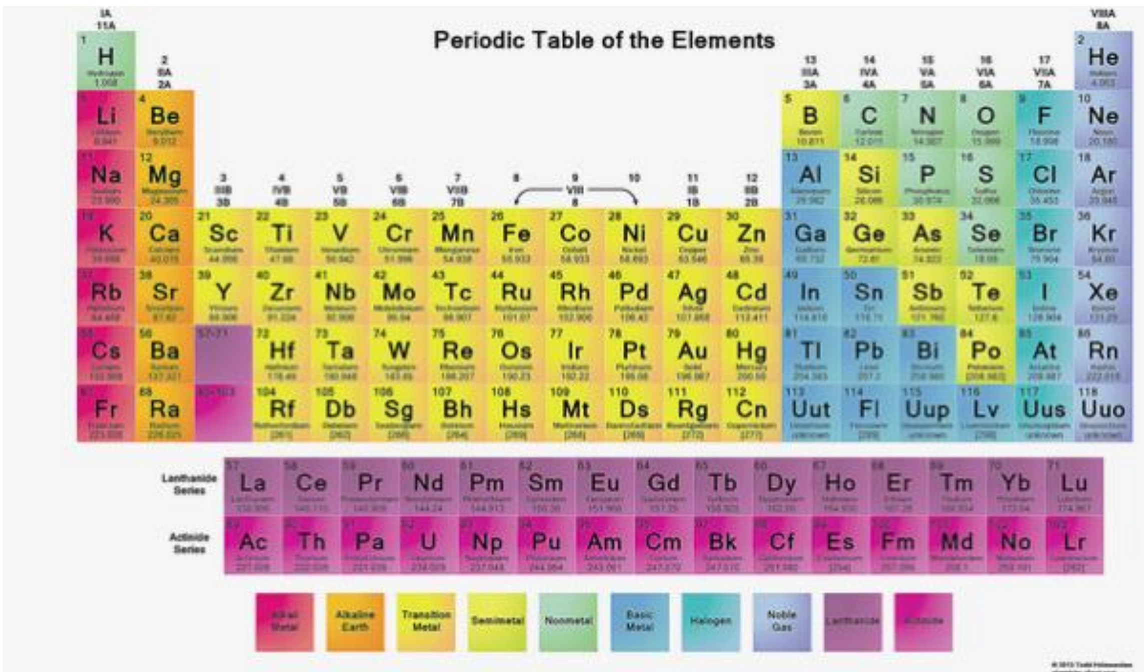

Figure 2 The periodic table of the elements

Referring to Figure 2, the elements in the left most column from the 2nd row on down are called the "alkali metals"—the left-hand column in dark pink. The top one of these is lithium, Li. All these alkali elements have one electron in their outer orbits. The electrons in the inner orbits shield this negatively-charged outer electron from all but one of the attractive, positively charged protons of the nucleus.

This means that the alkali elements, like lithium, can easily give up their outer electron, resulting in a positively charged ion, which is transported through the battery as illustrated in Figure 1.

[21] https://electrek.co/2021/08/09/tesla-battery-cell-material-recovery-new-recycling-process/

The lithium-based battery has thus been the most commercially developed battery. You might ask, though, why not use the next alkali metal down in this column, which is sodium, since sodium is vastly more abundant in the earth's crust than lithium. In fact, sodium-ion batteries have been, and are being, considered[22]. It turns out, however, that for the same amount of energy storage they are heavier, so sodium-ion batteries might be suitable where weight is *not* an issue, unlike the situation in electric cars. Another possibility is the element in the same row as sodium, Na, but one column over, namely magnesium, Mg. It, too, is being explored and in footnote 23 the advantages and disadvantages of magnesium are explored[23].

Concluding Remarks

This essay was prompted by a question originally posed to the two of us: "Is there enough lithium to meet the expected sharp rise in demand for Li-ion batteries as and when the internal combustion engine is replaced by electric vehicles?" We think the answer to this question is almost certainly **yes**. Rather, as far as the U.S. manufacturers of electric vehicles are concerned, the crucial goal is developing *more reliable current supplies* both domestically and from relatively politically stable countries such as Chile and Australia.

Extraction of the brine associated with U.S. geothermal sources seems to us an attractive option with likely less environmental damage than ore mining. But significant investment in expanding production from all these sources is required.

A similar question can be asked of cobalt and the answer is similar: It is not the total global reserves of cobalt. Rather, it is the heavy reliance upon the politically unstable Democratic Republic of Congo as the main cobalt source and China's ownership of a substantial fraction of the DRC cobalt mines, along with the significant environmental and societal impact of cobalt mining. Politically stable Australia is the most likely viable alternative. In contrast to lithium, however, a mitigating circumstance is that lithium ion batteries can be produced with substantially less cobalt by increasing the amount of nickel. Or, by use of cobalt-free iron-phosphate-lithium batteries where volume and mass energy density are less of an issue for energy storage applications and some EVs.

Finally, the prospects for recovery of critical materials by recycling seem promising as more and more batteries reach the end of their useful life. One obstacle is that it is still costly. Another obstacle is the lack of common packaging designs and composition materials, so that there is no 'one size fits all' recycling technology presently available. Since some of these design and composition mixes are proprietary, it is not clear when, if ever, a common recycling technology will be available.

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[22] https://pubs.acs.org/doi/10.1021/acsenergylett.0c02181
[23] https://www.anl.gov/article/qa-could-magnesium-be-a-battery-future-argonne-chemist-brian-ingram-weighs-in

Acknowledgements

We thank Hong Yang, of the UC Davis Energy and Efficiency Institute for calling our attention to the Dunn *et al.* paper on Li-ion recycling. Thanks also to Kim Shedd and Brian Jaskula of the National Minerals Information Center, U.S. Geological Survey, for clarifying the interpretation of the data and definitions used in the analysis.