LITHIUM-ION BATTERIES: EXAMINING MATERIAL DEMAND AND RECYCLING ISSUES

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Abstract

Use of vehicles with electric drive, which could reduce our oil dependence, will depend on lithium-ion batteries. But is there enough lithium? Will we need to import it from a new cartel? Are there other materials with supply constraints? We project the maximum demand for lithium and other materials if electric-drive vehicles expanded their market share rapidly, estimating material demand per vehicle for four battery chemistries. Total demand for the United States is based on market shares from an Argonne scenario that reflects high demand for electric-drive vehicles, and total demand for the rest of the world is based on a similar International Energy Agency scenario. Total material demand is then compared to estimates of production and reserves, and the quantity that could be recovered by recycling, to evaluate the adequacy of supply. We also identify producing countries to examine potential dependencies on unstable regions or future cartels.

Introduction

As the world energy community evaluates alternatives to petroleum for personal vehicles, every aspect of potentially important technologies must come under intense scrutiny. Technical and economic issues receive most of the attention, but material availability is important to consider whenever rapid growth is expected. Lithium-ion batteries are a very promising contributor to reducing our dependence on imported oil. But is there enough lithium? Will we need to import it from a new and unfriendly cartel? What about other battery materials? The adequacy of lithium supply was recently questioned by Tahil [1], but his conclusions were disputed by Evans [2]. In this paper, we explore the potential demand for lithium and other key battery materials if hybrids, then plug-in hybrids, and then pure electric vehicles expand their market share extremely rapidly[1]. This is not meant to be a projection, but rather an upper bound on the quantity of material that could be required. The total demand can then be compared to estimates of production and reserves, and quantities that could be recycled, to evaluate the adequacy of future supply.

Several steps are required to estimate total demand for materials. First, an estimate of total vehicle demand vs. time is combined with a scenario of percent of new sales by each technology vs. time to calculate the number of new vehicles of each type produced annually. Then, batteries are designed for each vehicle type and for each chemistry, and the percent of lithium (or cobalt, nickel, etc.) in each active material and the battery pack is calculated. The battery mass for each vehicle type is estimated, and the total annual requirement for each material calculated. Finally,

[1] We will refer to all three types as electric vehicles, or vehicles with electric drive.

materials potentially available via recycling are estimated to determine net virgin material required and compared to production and reserves.

Vehicle Demand

To estimate U.S. sales of vehicles with electric drive, we extended the Energy Information Administration (EIA) projections of light vehicle sales for the United States from 2030 [3] to 2050, using a model based on Gross Domestic Product, fuel price, and projections of driving-age population by using the VISION 2007 model [4]. Only moderate growth is projected between now and 2050, and most of that is in the light truck market. We took the most optimistic scenario for the penetration of vehicles with electric drive into the U.S. market from the DOE Multi-Path Study (Phase 1)[5]. In this scenario, 90% of all light-duty vehicle sales are some type of electric vehicle by 2050. This is an extreme-case scenario, not a projection. It represents the maximum percent of U.S. sales that could be accounted for by hybrid vehicles like those on the road today (HEV), plug-in hybrids with different all-electric ranges (PHEVX, where X is the all-electric range in miles), and pure electric vehicles (EVs). The maximum total annual sales of vehicles with electric drive occur in 2050, with 21 million units. The cumulative total for sales of all types of electric vehicle in the United States until 2050 is 465 million vehicles.

We relied on an IEA scenario [6] for world demand. IEA is developing scenarios of what would need to be done to meet IPCC CO_2-reduction goals, based on World Bank economic and UN population projections, and the relationship between these and car ownership. The IEA scenario characterizes an aggressive adoption of many advanced technologies; about 1.6 billion electric-drive vehicles have been built by 2050 in this scenario, with pure EVs accounting for over 20% of global sales. This is a key assumption that would cause high lithium demand. It contrasts with the Argonne optimistic scenario's 10%. Figure 1 shows our U.S. scenario, as well as IEA's projection of world LDV sales.

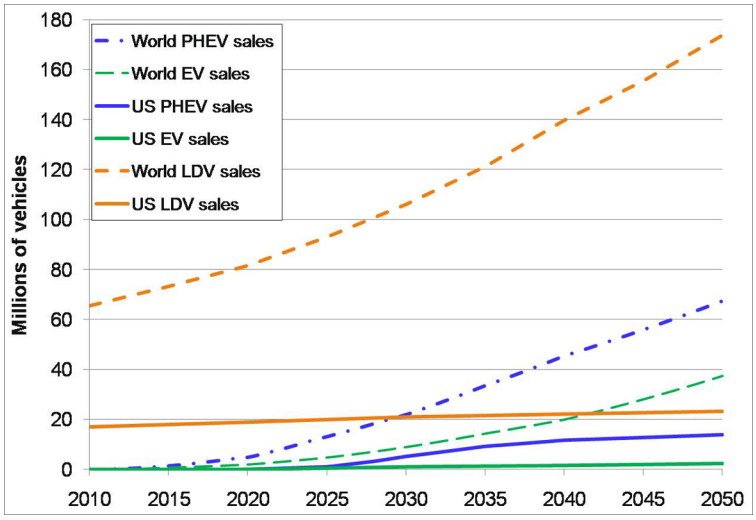


Figure 1. Light-Duty Vehicle Sales Projection to 2050

Batteries

Although the dominant chemistry used in electronics batteries today uses a mixture of nickel, cobalt, and aluminum (NCA) for the lithium salt in the active material for the cathode (positive electrode), numerous other materials are credible contenders for automotive batteries; any of them could become the major material used. We chose three promising chemistries, in addition to the current NCA graphite, to compare on the basis of material usage. These are defined in Table I. All contain lithium in a salt for the cathode active material and a lithium salt ($LiPF_6$) in the electrolyte solution. One also uses a lithium titanate salt, instead of the standard graphite, in the anode. For each battery chemistry analyzed, all materials in the electrodes and the electrolyte

were tabulated to give total material required. The actual chemical formulae were used to obtain elemental percents by weight in the active compounds.

Table I. Battery Chemistries Included in the Analysis

System→ Electrodes↓	NCA Graphite	LFP (phosphate) Graphite	MS (spinel) Graphite	MS TiO
Positive (cathode)	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	$LiFePO_4$	$LiMn_2O_4$	$LiMn_2O_4$
Negative (anode)	Graphite	Graphite	Graphite	$Li_4Ti_5O_{12}$

Four batteries were designed — one for each of the chemistries chosen — for each of three automobile all-electric ranges (a standard hybrid was simulated as a PHEV4). Battery designs assumed blended-mode operation, in which the engine can turn on to supply peak power demand during electric operation. Table II shows a partial breakdown of the material masses per cell. The table also shows total cell mass and numbers of cells required for each of the 12 cases.

From (1) the mass percent of each element in the active compounds and (2) the mass required of each compound in the batteries, we calculated the quantities of lithium and other materials required per battery pack. For lithium, the total is the sum of lithium from the cathode, the electrolyte, and the anode (for the cells with titanate anodes). The total requirement of lithium (on an elemental basis) for each car is shown in Table III. The electric vehicle battery requirement is based on an assumed 100-mile range. A longer range would increase both the material required and the cost to the extent that significant market penetration is unlikely. Our colleagues find that the benefit-to-cost ratio of added all-electric range for vehicles with electric drive drops very rapidly, casting doubt on the marketability of EVs with ranges greater than 100 miles [7].

Battery (and material) masses were scaled up from the designs for automobiles to ones appropriate for light trucks or sport utility vehicles, on the basis of computer runs using the Powertrain Systems Analysis Toolkit model [8], for the Multi-Path Study [9]. This is not a simple linear scale-up from the automobile masses because of the different performance features required.

Table II. Detailed Automobile Battery Composition

	Battery Type											
Parameter	NCA-G			LFP-G			LMO-TiO			LMO-G		
Vehicle Range (mi) at 300 Wh/mile	4	20	40	4	20	40	4	20	40	4	20	40
Materials Composition (g/cell)												
Cathode (+) active material	77	314	635	74	302	609	125	502	1,003	63	255	514
Anode (-) active material	51	209	423	51	208	419	83	334	669	42	170	342
Electrolyte	50	149	287	64	194	376	69	239	477	41	124	242
Total cell mass (g)	424	1,088	2,043	471	1,162	2,170	483	1,534	3,062	347	888	1,671
Cells per battery pack	60	60	60	60	60	60	60	60	60	60	60	60
Battery mass (kg)	31.2	75.9	140.1	34.6	81.6	150.2	35.6	106.2	209.1	26.1	62.6	115.4

Table III. Total Lithium Required per Passenger Automobile

	Battery Type															
Parameter	NCA-G				LFP-G				LMO-G				LMO-TiO			
Vehicle range (mi) at 300 Wh/mile	4	20	40	100	4	20	40	100	4	20	40	100	4	20	40	100
Vehicle type	HEV	PHEV	PHEV	EV	HEV	PHEV	PHEV	EV	HEV	PHEV	PHEV	EV	HEV	PHEV	PHEV	EV
Li in cathode (kg)	0.34	1.36	2.75	6.88	0.20	0.80	1.61	4.02	0.15	0.59	1.18	2.96	0.29	1.17	2.31	5.78
Li in electrolyte (kg)	0.04	0.10	0.20	0.51	0.05	0.14	0.26	0.53	0.03	0.09	0.17	0.43	0.05	0.17	0.34	0.84
Li in anode (kg)	0	0	0	0	0	0	0	0	0	0	0	0	0.30	1.21	2.43	6.07
Total Li in pack (kg)	0.37	1.46	2.96	7.39	0.24	0.93	1.87	4.68	0.17	0.67	1.35	3.38	0.64	2.54	5.07	12.68

Total Lithium Requirements and Reserves

Figure 2 shows how potential U.S. demand compares to historical world production and U.S. consumption (data from [10]). The U.S. consumption is perhaps misleading, since it only accounts for direct purchases of lithium compounds by U.S. firms and omits indirect consumption in imported batteries and products containing batteries. Once the total quantities of material required per vehicle by type were determined, they were multiplied by the annual vehicle sales by type to provide an estimate of the material demanded. Figure 2 also shows the U.S. results for lithium, assuming that all vehicles used the current NCA-Graphite chemistry. The demand is seen to rise to over 50,000 metric tons annually by 2050.

U.S. demand for lithium for automotive batteries has a very long way to go before it strains current production levels, with U.S. demand, even under this aggressive penetration scenario, not reaching current production levels until after 2030.

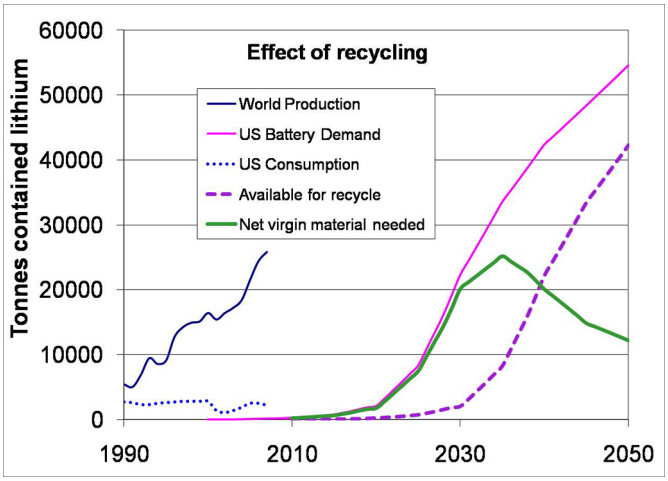


Figure 2. Future U.S. Lithium Demand Compared to Historical Production

We then considered the potential impact of recycling on net demand for materials. Figure 2 also shows the demand curve lagged by 10 years (assumed average battery life) to approximate material that would be available for recycling if all lithium were recycled. Finally, the graph shows the difference between the gross material demand and the potentially recyclable material. This represents the net quantity of virgin material that would be required if all battery material could be recycled. Note that this curve turns over, meaning that the quantity of virgin material required actually declines after about 2035, around the point at which it reached a maximum of

just under current production levels. The net demand turns around because the rate of demand growth slows. This demonstrates the importance of recycling.

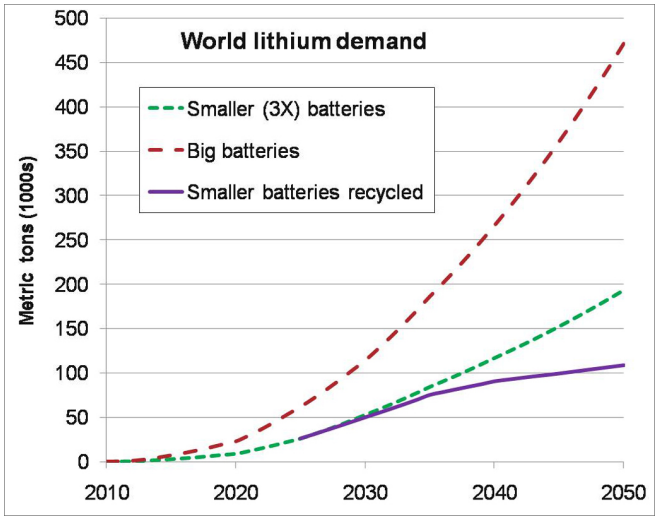


Figure 3. Future World Lithium Demand Scenarios

There are several reasons to expect that world demand will be considerably lower than the maximum shown in Figure 3. Smaller cars with smaller batteries than IEA assumed (12–18 kWh) are likely to be used. And, it can be argued that hybrids are more attractive than battery electric cars. Further, many of the vehicles could be electric bicycles or others that require less than 10% as much lithium per vehicle. With smaller batteries and recycling, net world demand in 2050 can be kept to 4 times current production.

We estimated cumulative battery demand for lithium under the assumption that all batteries were produced from only one chemistry. Total potential world lithium demand is shown in Table IV. (This was done for each of the four chemistries; NCA graphite is shown.) This total was then compared to several estimates of the world reserve base. The maximum demand (double the quantity shown) would occur if all batteries were made by using titanate anodes, since this chemistry uses the most lithium per battery. Only in that case does total demand exceed the USGS conservative reserve base estimate. However, by taking care with battery size and taking advantage of material that could be made available from recycling, enough lithium is available to use while we work toward an even more efficient, clean, and abundant means of supplying propulsion energy.

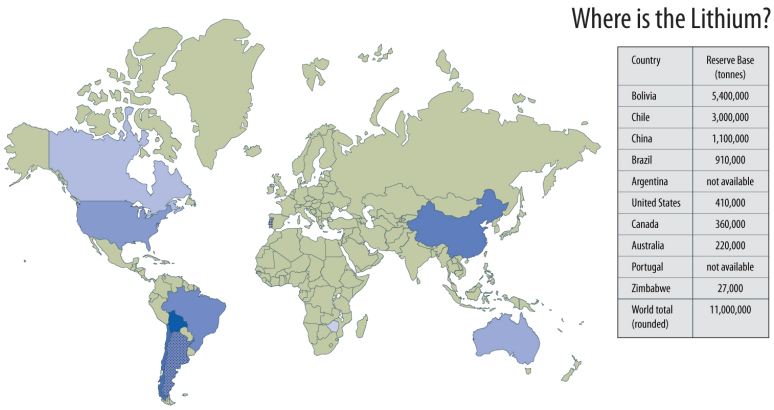
Table IV. World Lithium Demand and Reserves

Item	Cumulative Demand to 2050 (contained lithium, 1,000 metric tons)
Large batteries, no recycling	6,474
Smaller batteries, no recycling	2,791
Smaller batteries, recycling	1,981
USGS Reserves [11]	4,100
USGS Reserve Base [11]	11,000
Evans and others	30,000+

Figure 4 shows the locations of known lithium reserves. Chile dominates current production, with Australia second. Bolivia has huge untapped reserves, and China is rapidly developing its production capacity. The United States has limited reserves, and so it is likely to remain at least partially a materials importer, although batteries could certainly be produced here from these imported materials. The United States could supply much of its own needs and has relatively stable relationships with the major lithium-producing countries, and so significant supply problems are not anticipated.

Other Materials

Using the same scenario and methods described earlier for lithium, we estimated the potential demand for nickel, cobalt, and aluminum for NCA-graphite batteries; iron and phosphorus for LFP batteries; manganese for either the LMO-G or LMO-G; and titanium for the LMO-TiO. These quantities were then compared to USGS reserve data for each material, if appropriate. For some materials, such as iron, the quantity available is sufficiently large that another measure was used for comparison. Table V compares material availability to potential cumulative U.S. light-duty battery demand[2] to 2050 and estimates the percent that could be required. A potential constraint was identified for cobalt. If NCA-G were the only chemistry used, batteries use could impact the reserve base by 2050. Approximately 9% of the world reserve base could be required for U.S. light-duty vehicle batteries. World demand would be a factor of 4 larger. Of course, recycling — which is more likely with an expensive, scarce material — would significantly alleviate this pressure, as would the expected shift away from NCA-G to other chemistries.



Country	Reserve Base (tonnes)
Bolivia	5,400,000
Chile	3,000,000
China	1,100,000
Brazil	910,000
Argentina	not available
United States	410,000
Canada	360,000
Australia	220,000
Portugal	not available
Zimbabwe	27,000
World total (rounded)	11,000,000

Figure 4. Sources of Lithium [11]

The United States does not produce any cobalt, and so we must depend entirely on imports[3]. In 2006, "ten countries supplied more than 90% of US imports. Russia was the leading supplier, followed by Norway, China, Canada, Finland, Zambia, Belgium, Australia, Brazil, and Morocco [12]." Cobalt is produced in many other countries as well, so it is unlikely that any one country or group could manipulate supply or price. Similarly, the United States does not produce any nickel, except for a small amount as a by-product of copper and platinum/palladium mining, so we import from Canada (41%), Russia (16%), Norway (11%), Australia (8%), and other countries (24%)[13]. Again, the diversity of producers suggests security of supply. The remaining battery materials are all abundant.

Table V. Comparison of U.S. Light-Duty Battery Demand to Material Availability [12,13]

Material	Availability (million tons)	Cumulative Demand (million tons)	Percent Demanded	Basis
Co	13	1.1	9	World reserve base
Ni	150	6	4	World reserve base
Al	42.7	0.2	0.5	U.S. capacity
Iron/steel	1,320	4	0.3	U.S. production
P	50,000	2.3	~0	U.S. phosphate rock production
Mn	5200	6.1	0.12	World reserve base
Ti	5000	7.4	0.15	World reserve base

[2] Assuming that all batteries were made by using only the chemistry requiring the material

[3] A fraction of current supply comes from the stockpile and recycling, but any new supply will be imported.

Recycling Processes

Recycling can recover materials at different production stages, all the way from basic building blocks to battery-grade materials. At one extreme are smelting processes that recover basic elements or salts. These are operational now on a large scale and can take just about any input, including different battery chemistries (including Li-ion, Ni-MH, etc.) or mixed feed. Smelting takes place at high temperature, and organics, including the electrolyte and carbon anodes, are burned as fuel or reductant. The valuable metals (Co and Ni) are recovered and sent to refining so that the product is suitable for any use. The other materials, including lithium, are contained in the slag, which is now used as an additive in concrete. The lithium could be recovered by using a hydrometallurgical process [14], if justified by price or regulations.

At the other extreme, recovery of battery-grade material has been demonstrated. Such processes require as uniform feed as possible, because impurities in feed jeopardize product quality. The components are separated by a variety of physical and chemical processes, and all active materials and metals can be recovered. It may be necessary to purify or reactivate some components to make them suitable for reuse in new batteries. Only the separator is unlikely to be usable, because its form cannot be retained. This is a low-temperature process with a low energy requirement. Almost all of the energy and processing to produce battery-grade material from raw materials is saved. Large volumes are not required [15].

Battery use is expected to grow much more rapidly than any other use, so batteries will dominate lithium demand in the future. Further, growth in demand for batteries for electric-drive vehicles will dominate the battery demand [16], and so auto batteries will dominate demand for lithium after 2020. Therefore, it will be desirable to use recovered materials back in batteries.

Conclusions

Potential material supply constraints should be considered before embarking on an ambitious program of development for any new technology. However, shortages have often been forecast without adequate exploration or consideration of incentives rising prices might provide. For example, in 1972 the Club of Rome warned that the world would run out of gold by 1981; mercury and silver by 1985; tin by 1987; and petroleum, copper, lead, and natural gas by 1992 [17]. In the case of materials for lithium-ion batteries, it appears that even an aggressive program of vehicles with electric drive can be supported for decades with known supplies, if recycling is instituted. Of course, larger vehicles with longer ranges require more material, and so heavy reliance on pure electrics could eventually strain supplies of lithium and cobalt. Further work is required to examine recycling in more detail and to determine how much of which materials could be recovered with current or improved processes. Environmental impacts of both production and recycling processes should be quantified as well.

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