# Battery Materials Value Chains

***Demand, Capacity and Challenges***

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## ABSTRACT

Our research premise is that demand for battery materials would hinge on battery chemistry driven by applications, within a context of extractive industry dynamics. Our analysis indicates that 75% utilization rates at existing production capacity coupled with upcoming projects can satisfy most of the expected demand for both lithium and cobalt in the short run. However, high-growth scenarios require new capacity and/or significantly higher rates of utilization in existing facilities. The influence of geopolitical risks, growth in other applications, and development of new applications could push demand in excess of production capacity. Government regulations in response to local interests, environmental concerns and future sustainability have influenced material supply in the past and may continue. While many factors could ease pressure for new production capacity, development of new applications like grid-energy storage and use of lithium-ion batteries in heavy vehicles have the potential to significantly increase demand beyond what is typically expected in the literature. Lithium will continue to be a crucial component of batteries, but battery end-uses may shift as the tolerance to different conditions affects energy storage materials strategies.

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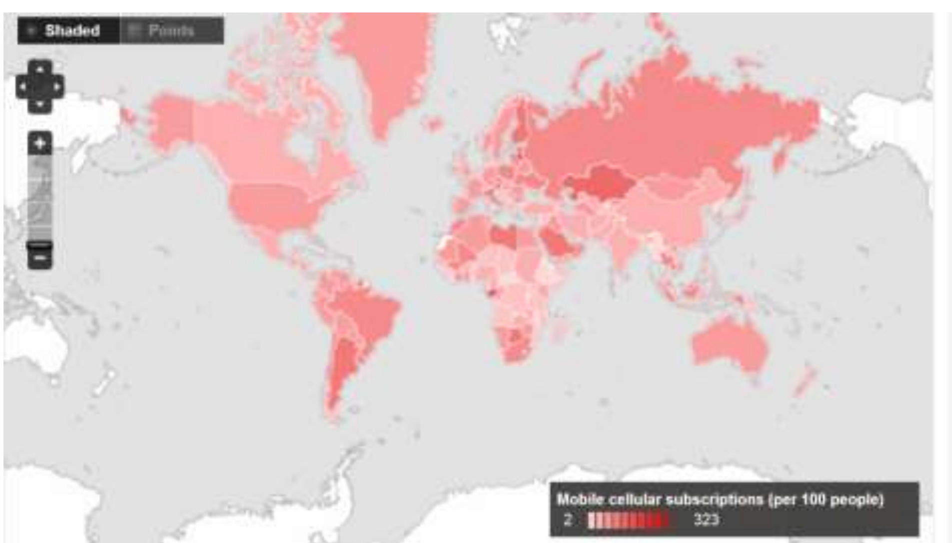
## BACKGROUND FOR THIS RESEARCH NOTE

By any measure, prevailing views are that alternative energy technologies and systems represent improvements over conventional energy resources and designs, particularly those that depend upon fossil fuels. It is commonly and widely believe that alternative energy schemes will present benefits in both environmental improvement and energy security. These beliefs drive policymaking and regulation to promote alternative energy options. Voters, taxpayers and energy consumers are encouraged, including through financial incentives, to support them. One of the substantial unknowns is the materials requirements for alternative energy systems. Whether it is balancing intermittent renewable energy sources like wind and solar or to power electric or hybrid electric vehicles for mobility, the expectation – indeed the "black box" in any alternative energy scheme - ultimately rests on some form of energy storage and release. Often energy storage and release is in the form of commercial battery designs. The research community has done little to map out the value chain economics and associated challenges that underlie the supply of basic materials for commercial battery designs to support alternative energy technologies and systems. These challenges deserve more substantial research and transparency. They include a wide range of considerations, such as legal, regulatory and fiscal frameworks for access to minerals resources for exploitation; associated environmental considerations (on a full, life cycle basis); geopolitical and supply security risks. It would not make sense for societies to pursue energy technology options that impose net costs over conventional energy systems and yet that outcome is a distinct possibility.

People use batteries for energy storage and release worldwide, every day. The prolific growth and widespread access of cellular telephones means that, at a minimum, at least some people in all countries have access to the energy storage medium most commonly associated with modern consumer products – the lithium based battery design that is present in every handheld device. We tend to regard mobile telecommunications a key indicator of economic development (see the World Bank example below). Mobile telecoms is a powerful enabling technology, allowing societies to leapfrog landline systems and putting the internet information age at the fingertips of even the most disadvantaged economies.

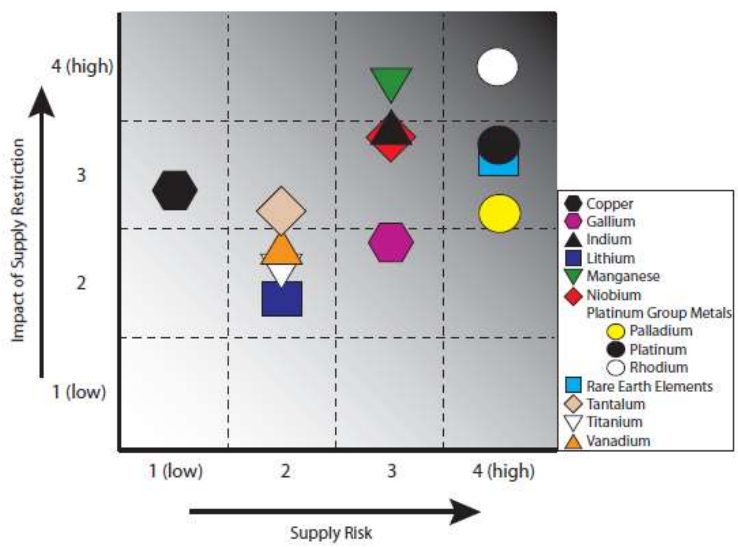
**Figure 1. Mobile Cellular Subscriptions per 100 People, 2011-2015**




*Source: World Bank, http://data.worldbank.org/indicator/IT.CEL.SETS.P2/countries?display=map; because this indicator omits some forms of subscription access cellular access is underestimated.*

Clearly, there is "no going back" once advances such as mobile telecoms take hold. Many observers view alternative energy approaches, especially in the form of distributed generation (ranging from roof top solar systems to small-scale fuel cells) to represent a similar leapfrog potential.  This would afford societies not only improved access to energy, addressing many other dilemmas in human development along the way, but a path around the inevitable scale up of conventional energy systems with associated emissions. Detecting the need for a better understanding of minerals criticality, the National Research Council undertook an effort to draw attention to the understudied or undocumented tradeoffs. The "criticality matrix" devised for the NRC study focused on supply security of selected minerals for a range of applications including energy. This kind of approach offers a template for thinking through the myriad and, in many cases, substantial risk factors that would entail scale up of non-fuel minerals extraction and supply to satisfy the kinds of dramatic expansions of alternative energy systems that some envision.

**Figure 2.  Criticality Matrix for All Mineral Evaluated in NRC Study (2008)**

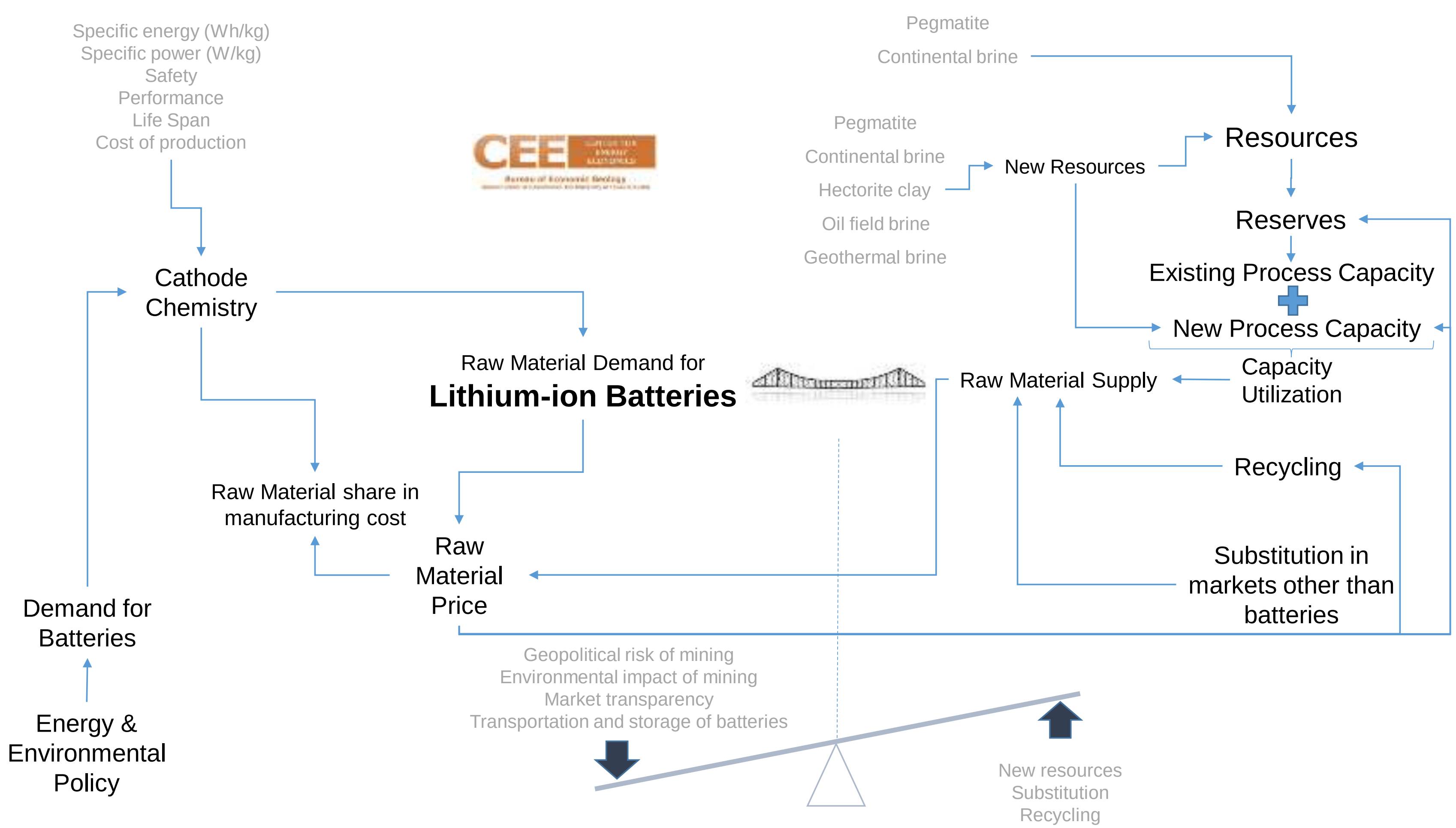



*Source: NRC (2008)*

In the following sections, we analyze the current supply and utilization of lithium based batteries. We consider the economics and value chain structures for two of the minerals, lithium and cobalt. Figure 3 represents our "research map" for this effort and for ongoing work. Since initiating this research note, a number of publications have addressed recent developments in lithium including price moves (for instance see Atacama, 2016).[1] Our interest is in the relationships between the demand and supply of raw materials needed for lithium-ion battery (LIB) designs. We look at material composition, characteristics of different designs, and outlook for future chemistry to reach at raw material demand. We take a longer-term view but as a research organization and team steeped in the extractive industries, all of us at BEG/CEE are well versed in sort term disruptions that can happen when supply and demand imbalances occur. Policy and regulatory induced imbalances are well-documented for the conventional energy value chains, including in our own work.

[1] Liam Denning captures prevailing views and sentiments in "If You Liked Palladium, You'll Love Lithium", February 26, 2016, Bloomberg Gadfly, http://www.bloomberg.com/gadfly/columnists/ASe2HvynvWg/liam-denning/articles/2016-02-26/lithium-electric-car-demand-tight-supplies-will-drive-boom.

**Figure 3. Understanding the Demand and Supply for Lithium**

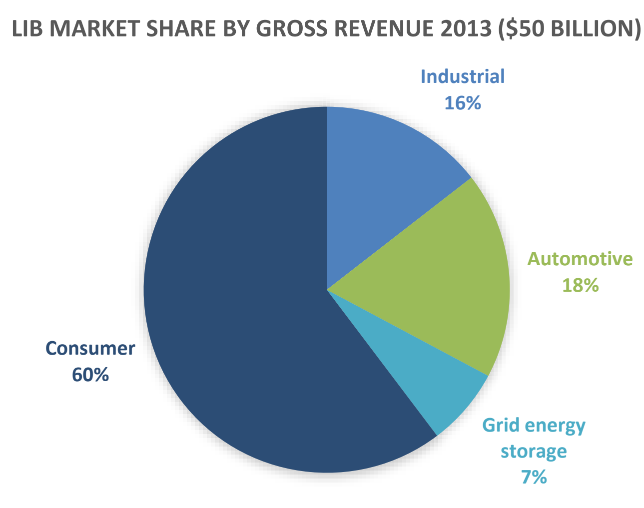


## INTRODUCTION

Advances in battery design significantly affect the growth of battery demand, which influences raw material demand. To match the projected scenarios of LIB demand, we investigate available resources, reserves, and processing capacities of raw materials around the world. Several factors collectively determine whether our projected gap between demand and supply of raw materials can be bridged in a timely manner given the uncertainties associated with geopolitical risks in resource-rich countries, environmental impacts of mining, and market transparency. The development of new resources, recycling, and material substitution will relieve some of the pressures on proving new reserves and expanding processing capacity, along with the global supply chain of lithium and other key minerals

Since their first commercialization in 1991, lithium-ion batteries (LIBs) played a dominant role in energy storage for portable consumer applications such as mobile phones, laptops, and cameras. By 2013, portable consumer applications still dominate the LIB market segments by revenue, followed by automotive, industrial, and grid-energy storage applications, respectively (Figure 4).[2] Many expect this distribution to change in the future as countries pursue electric vehicles (EVs) for the intended purposes of reducing local emissions, diversifying energy portfolios, and reducing fuel imports among others. Some studies also claim reduction of life-cycle greenhouse gas (GHG) emissions by switching from a traditional internal combustion engine vehicle to an EV.[3] However, Lomborg (2013) and Li and others (2014) claim that the environmental impacts of the mineral supply chain from mine to transport, and from battery manufacturing to recycling, are not fully understood. The International Energy Agency (IEA) modeling requires more than 7 million EV sales per year by 2020 to meet greenhouse gas (GHG) emissions goals (IEA, 2011).This goal is an aggressive target when compared with actual sales of 300,000 EVs in 2015 (IEA, 2015). Due to projected growth in EVs and variations in battery chemistry, we expect changes in market shares of LIBs, raw material demand, and mineral value chain linkages, as depicted in Figure 4 below.

**Figure 4. Revenue Shares of Lithium-Ion Battery Market Segments**




*Source: Frost and Sullivan (2014)*

[2] The prices of batteries are different in different sectors; as such, these shares do not translate into volume shares. We provide those estimates later.

[3] For example, see Noshadravan and others (2015).

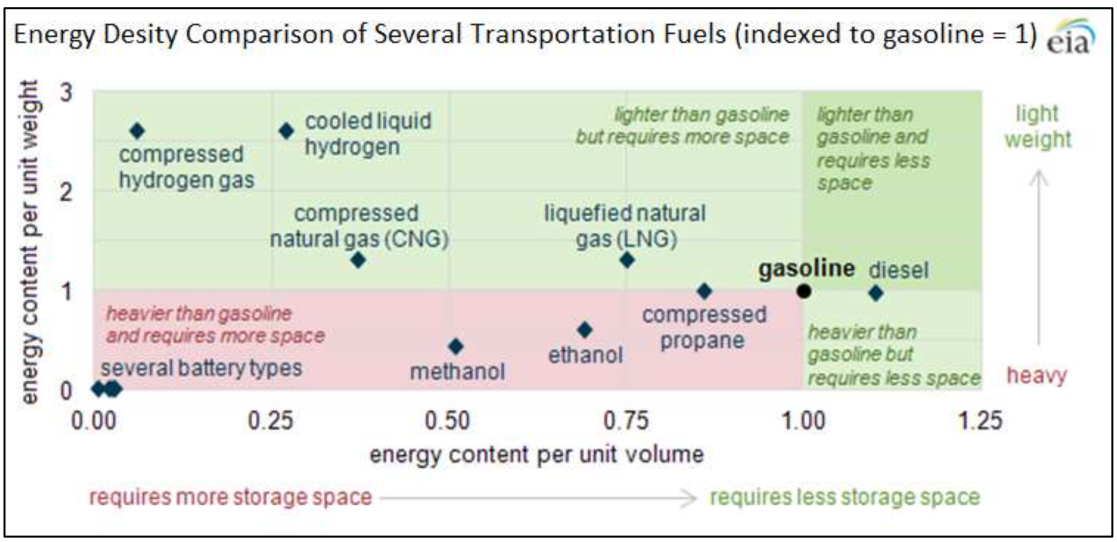
*Note: Industrial applications refer to healthcare, power tools, and military uses.*

The pace of demand growth for EVs depends on the robustness of the supply chains of lithium and other key minerals (e.g., cobalt) for the manufacture and deployment of EV batteries. Constraints include the availability of resources in desirable geographies, their reserves and production capacity, cost and timing of expanding capacity, existing logistics infrastructure, and the ability to expand such infrastructure. The ability to meet these requirements depends on commercial frameworks offered by resource owners including laws regulating access to resources, fiscal terms that determine financial viability of projects, and other key conditions. *In other words, battery storage materials for transportation or any other application, along with important non-fuel mineral inputs that are vital for any economic output, are subject to the same dynamics as oil, natural gas, and other resources for energy fuels.*

## LITHIUM-ION BATTERY: COMPOSITION AND DESIGN

The LIB industry has made significant advances especially for batteries used in the information-technology and consumer-electronics sectors. Energy density has tripled and costs have come down twenty-five-fold in the past two decades. Since 1992, energy density of a typical LIB 18650 cell has improved from 200 Watt-hour/Liter (Wh/L) to more than 600 Wh/L (Yoshino, 2015). Despite the improvements, the energy density of LIB is 6% of gasoline's energy density for an average internal combustion engine.[4] Figure 5 illustrates the relative position of batteries in terms of energy density.

**Figure 5. Energy Density Disadvantage of Batteries**




*Source: U.S. Energy Information Administration*

Since 1992, the cost of production decreased from over US$5,000/kWh to US$200/kWh (Yoshino, 2015). Providing "motive" power and sufficient range for a vehicle present different kinds of challenges affecting the ability to scale up the battery size (weight drags on EV performance) and density (impacting range) while improving cost competitiveness.

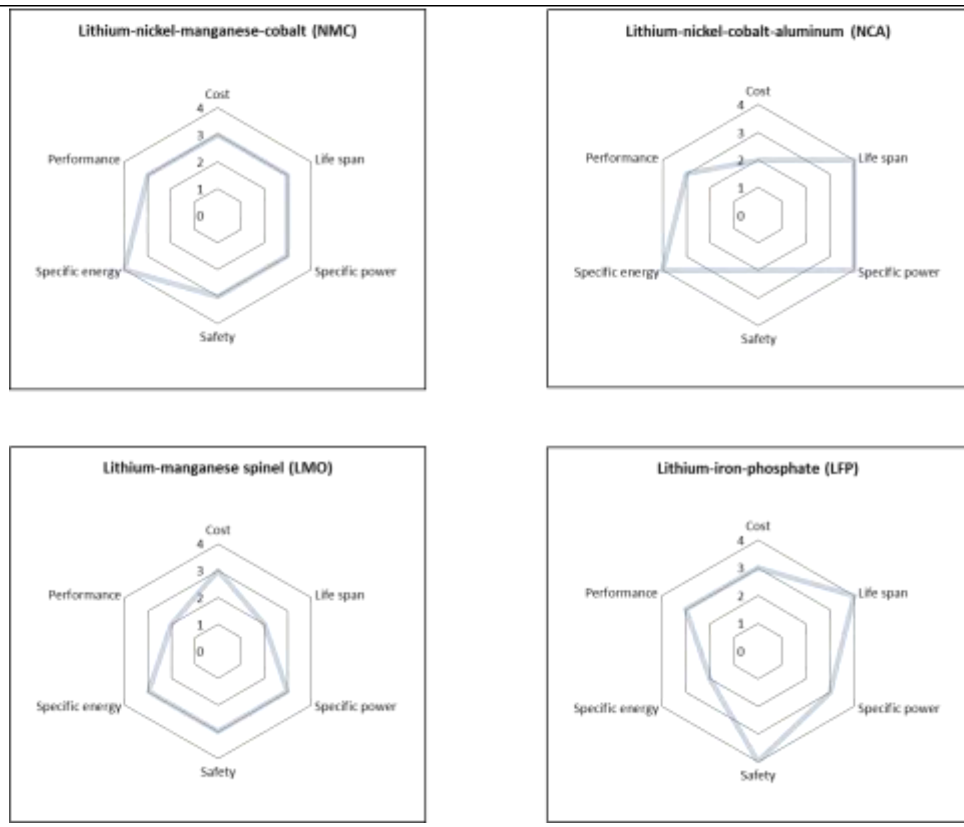
Four basic components that form LIBs are cathode, anode, electrolyte, and separator. The cathode is the positive terminal of a LIB, and is a transition metal oxide containing lithium-ion that constitutes the highest component in terms of weight up to 41% ( Gaines, L. and Cuenca, R., 2000) and material cost of

[4] However, different battery technologies, charging behavior, and ambient conditions might lead to different energy density estimates, ranging from 2% to 15% of gasoline's energy density.

about 36% (Roland Berger, 2011). Development of a variety of LIB chemistries results in differences and tradeoffs of battery characteristics (Figure 6).

Lithium-nickel-manganese cobalt (NMC) has a more balanced and relatively high ranking across all characteristics; and is fast emerging as the most popular cathode for EVs as noted by Fahrenbacher (2015). Lithium-iron-phosphate (LFP) has the highest rating (4 out of 4) on safety and lifespan but trails in specific energy (2 out of 4), which is crucial for EVs. Lithium-managanese spinel (LMO) has a short lifespan and inferior performance rating (2 out of 4) with 3 out of 4 ratings on other parameters. Lithium-nickel-cobalt-aluminum (NCA) is another popular chemistry with highest ratings on lifespan, specific power, and specific energy; and 3 out of 4 for performance, but NCA costs more to manufacture as compared to other cathode chemistries. Not shown in Figure 6 is Lithium-cobalt-oxide (LCO), considered unsuitable for electric vehicles due to low safety performance, however it remains in use for major consumer electronic applications.

**Figure 6. Comparison of Cathode Chemistries**

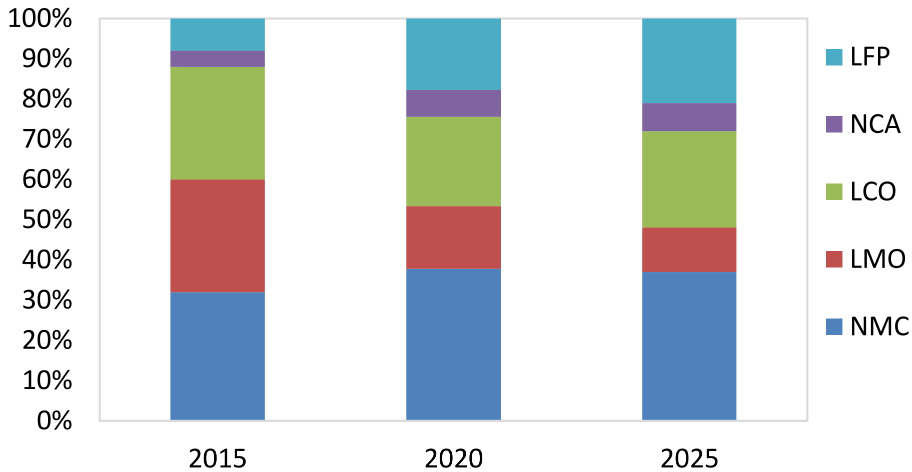



*Source: The Boston Consulting Group (2010)*

**Notes:**
The rankings are relative on a scale of 0 to 4, where 4 is the most preferred and 0 is the least.
*Safety*: The most important concern is for fire hazard due to thermal runaway, which occurs by overcharging, too high discharge rates, or short circuit. Batteries with rating of 4 are least prone to such incidents
*Specific energy*: The capacity of batteries to store energy per kilogram of mass. Specific energy limits the range of electric vehicles and is crucial for electric vehicles.
*Specific power*: Capacity of batteries to deliver power per kilogram of mass. This plays crucial role in Hybrid electric vehicles.
*Life span*: A batteries life span depends on cycle stability and overall age. Cycle stability is the number of times a battery is fully charged and discharged before its full charge capacity is 80% of the original.
*Performance*: Delivery of similar range of discharge and life in actual conditions. Batteries are optimized for low or high temperature, and are susceptible to lower than expected performance outside the optimized range of temperature.

Figure 7 shows current and expected production share of various battery chemistries (Schmid and Pillot, 2014). Based on performance observations in Figure 6, the NMC battery design is expected to grow in total cathode production share while LMO will drop significantly over the next decade. Shares of NCA and LFP types are expected to grow and the share of LCO remains the same.

**Figure 7. Production Shares of Cathode Chemistries**




The anode is the negative terminal, a carbonaceous material like graphite except in cases where lithium-titanium-oxide (LTO) is used (Gaines and Nelson, 2009; Yoshino,2015). Electrolytes are organic solvents with lithium salts and facilitate lithium-ion movement from cathode to anode while discharging. The separator is commonly a polyolefin membrane that prevents contact between cathode and anode (Pistoria, 2014).[5]

Different cathode chemistries have significant impact on raw material requirements as metal content varies widely. For example, LCO has only lithium and cobalt with weight percentages of 7% and 60% respectively, while NMC has about 7% lithium, 20% nickel, 19% manganese and 22% cobalt relative to total weight (Gaines and Nelson, 2009).

Table 1 shows metals content for a typical plugin-hybrid vehicle (PHEV20) with a 20-mile (32-km) range using NCA and NMC, the two most popular chemistries for lithium-ion cathode, and a graphite anode (Gaines and others, 2011). Since the growth rate of LIB applications in the automotive sector could exceed 20% on an annual basis (Deutsche Bank, 2011; SignumBOX, 2012), demand for the metals listed in Table 1 will have the greatest impact on materials supply chains.

[5] Besides the four fundamental components, aluminum and copper are used as current collectors and for battery casing, forming another significant use of materials.

**Table 1. Material Content for Lithium-ion Battery for Plug-in Hybrid (PHEV20)**

| **Battery** | **NCA-Graphite** | | **NMC-Graphite** | |
|---|---|---|---|---|
| Cathode | $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ | | $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ | |
| Anode | Graphite | | Graphite | |
| **Total battery mass (kg)** | | **75.9** | | **75.9** |
| ***Material Share in total mass*** | | | | |
| | *Percentage Share* | *Mass (kg)* | *Percentage Share* | *Mass (kg)* |
| Cathode | 24.8% | 18.82 | 24.8% | 18.82 |
| *Lithium* | 1.9% | 1.44 | 1.8% | 1.35 |
| *Cobalt* | 2.3% | 1.75 | 5.1% | 3.83 |
| *Manganese* | 0.0% | 0.00 | 4.7% | 3.57 |
| *Aluminum* | 0.3% | 0.23 | 0.0% | 0.00 |
| *Nickel* | 12.1% | 9.18 | 5.0% | 3.82 |
| *Oxygen* | 8.3% | 6.30 | 8.2% | 6.21 |
| Anode | 16.5% | 12.52 | 16.5% | 12.52 |
| *Graphite* | 16.5% | 12.52 | 16.5% | 12.52 |
| Copper parts | 13.3% | 10.09 | 13.3% | 10.09 |
| Aluminum parts | 12.7% | 9.64 | 12.7% | 9.64 |
| Aluminum casing | 8.9% | 6.76 | 8.9% | 6.76 |
| Steel | 0.1% | 0.08 | 0.1% | 0.08 |
| Carbon | 2.4% | 1.82 | 2.4% | 1.82 |
| Binder | 3.8% | 2.88 | 3.8% | 2.88 |
| Electrolyte solvent | 11.7% | 8.88 | 11.7% | 8.88 |
| Plastics | 4.2% | 3.19 | 4.2% | 3.19 |
| Thermal Insulation | 1.2% | 0.91 | 1.2% | 0.91 |
| Electronic parts | 0.3% | 0.23 | 0.3% | 0.23 |

## *Critical Metals*

Table 2 shows the materials requirements using NMC chemistry to meet an aggressive scenario of 7 million PHEV20 sales in 2020 (International Energy Agency, 2011). Since fully electric vehicles (EVs) have larger batteries and consume more material per vehicle class, using the PHEV20 as a baseline provides a conservative estimate since current plug-in hybrid vehicles have smaller batteries. Using the PHEV20 model clearly demonstrates the critical metals necessary for production. An increased production of EVs, larger EVs, and PHEVs requires more materials per vehicle type.

**Table 2. Material Sensitivity for Demand Growth**

| **Metal** | **Raw material requirement for 140,000 PHEV20 (2014 level) (metric tons)** | **Raw material requirement for 7 million PHEV20 (2020) (metric Tons)** | **Actual production in 2014 (metric tons)** | **2020 Material requirement share if production remains unchanged (%)** |
|---|---|---|---|---|
| Lithium | 190 | 9,480 | 36,000 | 26.3% |
| Cobalt | 537 | 26,832 | 112,000 | 24.0% |
| Nickel | 534 | 26,723 | 2,400,000 | 1.1% |
| Copper | 1,413 | 70,663 | 18,700,000 | 0.4% |
| Aluminum | 2,295 | 114,761 | 49,300,000 | 0.2% |
| Manganese | 500 | 25,016 | 18,000,000 | 0.1% |

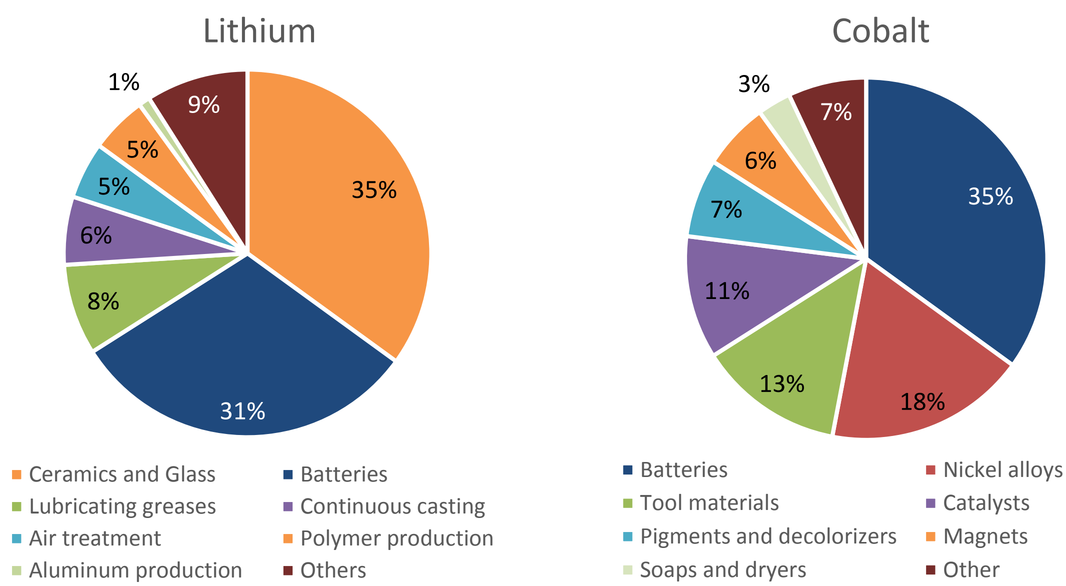
*Source: CEE estimates based on published information.*

Currently, metals and other commodities (and associated prices) are in oversupply as global economy and trade struggle following the recession in 2009, and new signs of weakness emerge from fast-growing economies of the last 15 years such as China. Commodity cycles are highly volatile and disruptions in supply-demand balances are expected. The combination of low prices, capital budget cuts for development of new supply capacity, and unattractive commercial frameworks for natural resource extraction may result in higher materials prices and supply delivery difficulties.

## DEMAND SCENARIOS

Figure 8 shows the various applications of lithium and cobalt in 2013. The ceramics and glass industry sector is the major consumer of lithium using 35% of total global production, closely followed by lithium-ion batteries at 31%. Manufacturing of lubricating grease, polymers, and primary aluminum are other major consumers of lithium as well as continuous steel casting and air treatment. Battery construction uses about 35% of total cobalt production, including nickel-cadmium, nickel-metal hydride, and lithium-ion battery designs. Other major applications for cobalt are nickel alloys, tools materials, catalysts, pigments, magnets, and soaps and dryers.

**Figure 8. 2013 End Use Applications of Lithium and Cobalt**
**Lithium Total: 34,000 metric tons; Cobalt Total = 110,000 metric tons**




*Sources: Roskill Information Services (2014); Jaksula (2015); Shedd (2015).*

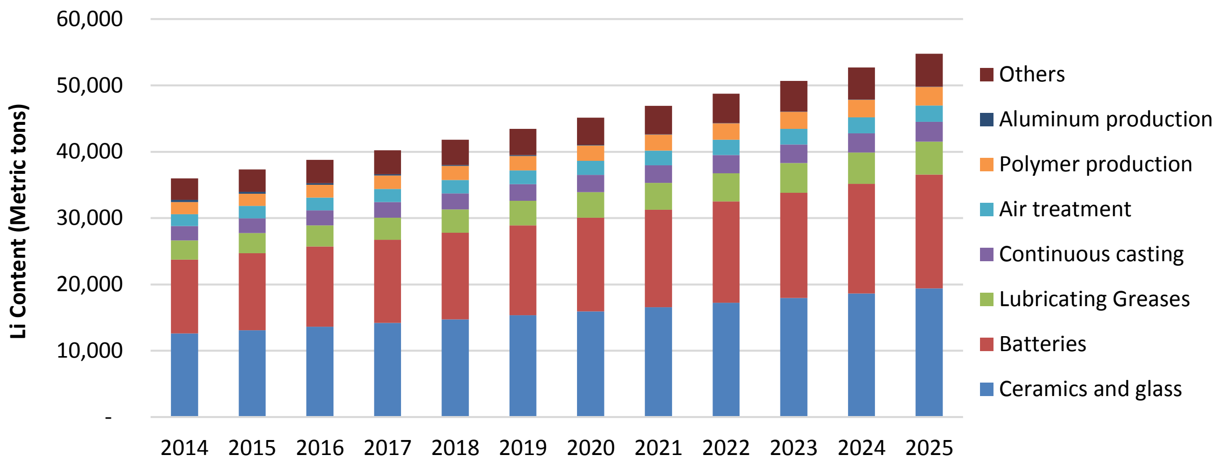
Industry analysts report three possible scenarios of growth in demand for batteries. These scenarios calculate lithium and cobalt demand based on annual expected growth in their respective applications. Change in consumption in one market may affect consumption in other markets. For simplicity, we assume that lithium demand in all industries other than batteries grows at same rate in all scenarios: ceramics and glass grow annually by 4%, lubricating greases by 5%, continuous casting by 3%, air treatment by 3%, polymer production by 4%, and other uses by 4%. Lithium demand in the aluminum industry declines at 20% per year. This decline occurs owing to a shift towards the prebaked electrolytes manufacturing process that reduces the use of lithium (Tabereaux, 2000; Merriman, 2012).

There is a huge variation in cobalt content over numerous battery chemistries. Based on the ratio of different cathode chemistries over the next ten years estimated by Schmid and Pillot (2014), and with the known quantity of materials in all chemistries from Pistoria (2014), it is possible to estimate an annual relationship between lithium and cobalt consumption for batteries. By varying lithium demand for batteries in the scenarios, cobalt consumption in lithium-ion batteries may be estimated. For markets other than batteries we assume a constant annual growth of 4% in demand for cobalt.

## Low Demand Scenario

This scenario has an expectation of static growth in batteries while assuming lithium demand grows annually by 4%, the average rate of all other lithium markets (Figure 9). The projection of demand is in terms of lithium content as all applications use a variety of lithium compounds.

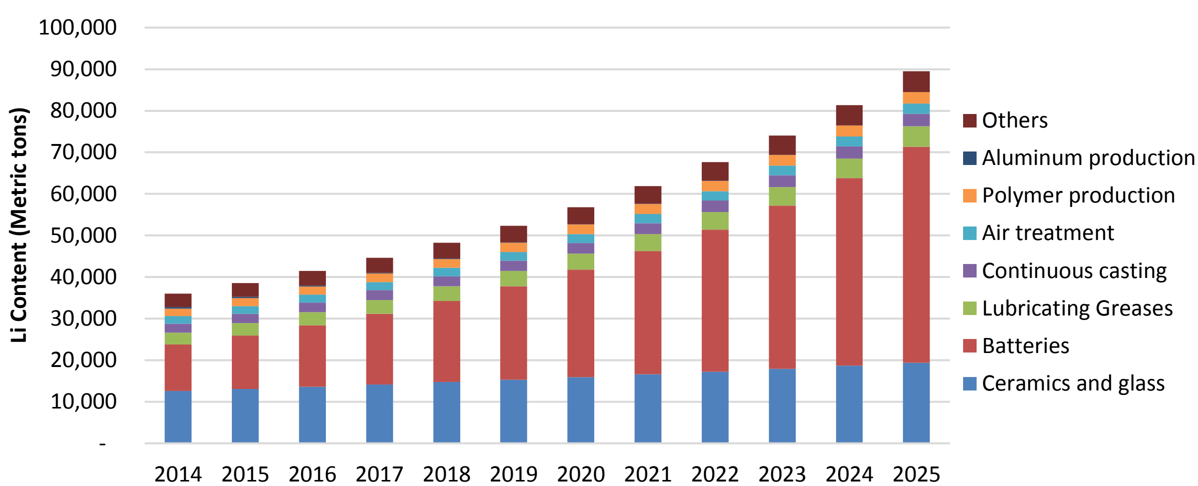
**Figure 9. Battery-Driven Lithium Demand: Low Scenario**




## Base Case Demand Scenario

This case assumes a 15% annual growth rate for batteries and a 4% annual growth rate for all other markets (Figure 10). Many market reports indicate growth rates within this range. A large portion of 2015 lithium demand comes from batteries in this scenario.

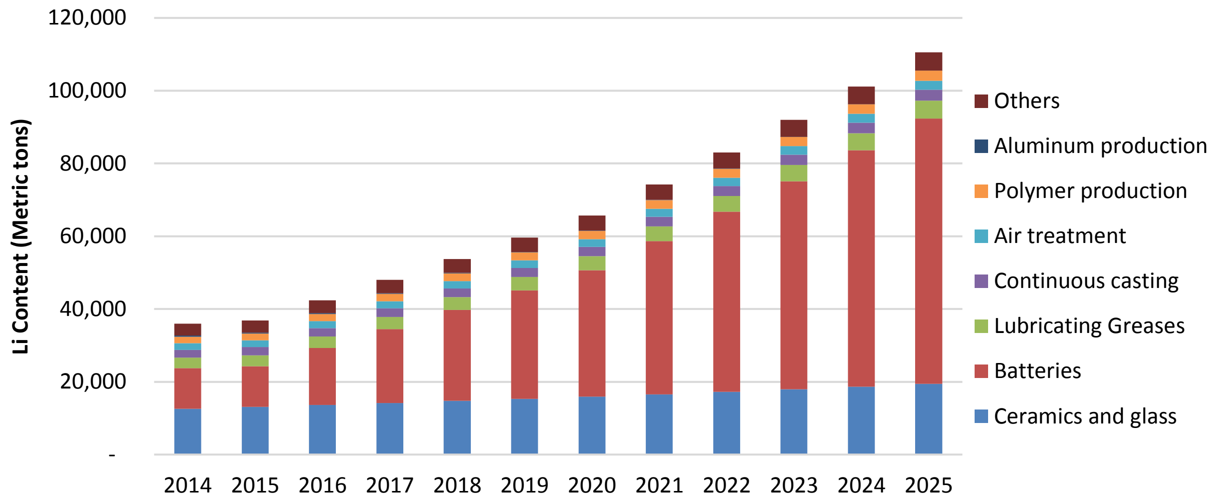
**Figure 10. Battery-Driven Lithium Demand: Base Scenario**




## High Demand Scenario

The high demand scenario reflects high growth in lithium use for batteries in EV applications (Figure 11). Uses of lithium for applications other than batteries grow at the same rates as in other scenarios. Lithium consumption for batteries in EVs and other applications have separate calculations to reflect a case of aggressive growth in EVs. It is possible to make an inference of the number of batteries and the total quantity of lithium required for EVs is from the target number of EV production in IEA (2011). For other battery applications, there is an assumption of an annual growth rate of 10% as estimated by SignumBOX (2012). The high demand case reflects a significant increase in EV production.

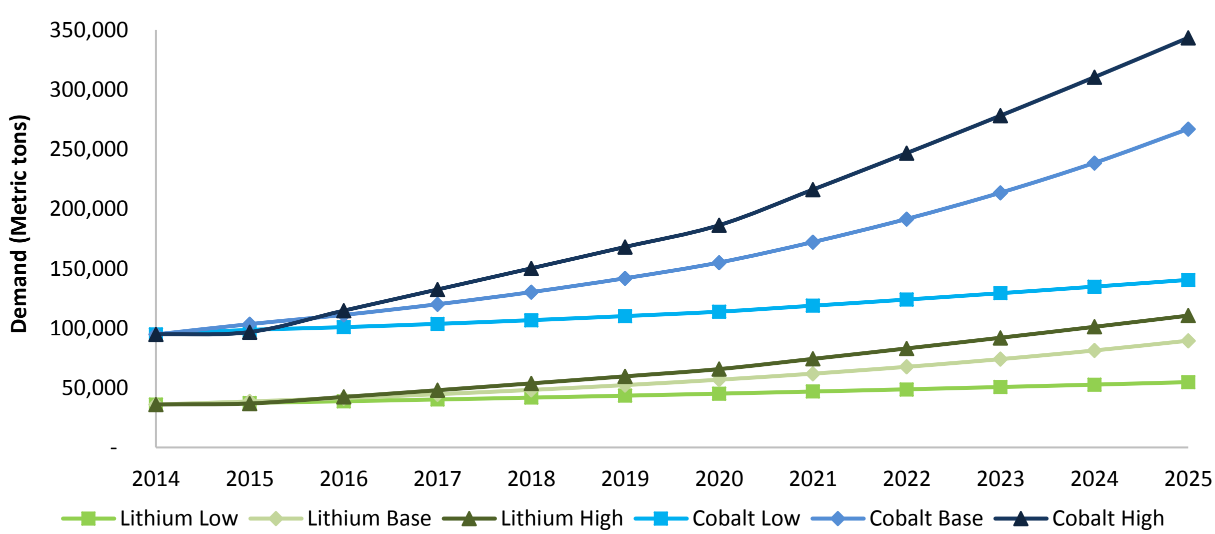
**Figure 11. Battery-Driven Lithium Demand: High Scenario**




## *Net Raw Material Demand*

The scenarios illustrated in Figure 12 require increases in annual production of lithium and cobalt from the 2014 levels as shown in Table 2. Cobalt demand for batteries is not a linear function of lithium use because of an expected shift after 2020 towards cathode chemistries that consume less cobalt, as shown in Figure 7.[6] The Base Case would nearly double the 2014 levels and the High Case would triple for both lithium and cobalt.

**Figure 12. Lithium and Cobalt Demand Outlook**




[6] From the data in Figure 7, we calculated lithium-to-cobalt ratio for every year in order to infer cobalt demand growth as a function of lithium demand growth.

## RESOURCES AND SUPPLY TO MEET DEMAND SCENARIOS

### *Lithium*

Traditionally, lithium is a product of mining from two types of sources: hard rock pegmatite sources and brine from continental salt lakes. Australia, China, Canada, Brazil, and the United States have the known major resources of pegmatite sources. Brine sources are mainly concentrated in Bolivia, Chile and Argentina, but significant concentration exists in China and the U.S. (Table 3). Bolivia has yet to start production, despite holding the highest percentage of world's known resources. Chile and Australia are the world's leading producers and exporters of lithium, while Chile holds more than 50% of the world's reserves.[7] Bolivia, Chile and Argentina collectively hold almost 58% of the world's resources.[8] The low cost of production in Salar de Atacama, Chile's main source of lithium, make Chile's resources counted as reserves (Yaksic and Tilton, 2009).

**Table 3. Lithium Reserves and Production Distribution**

| Country | Production 2014 (metric tons) | Reserves (metric tons) | Resources (metric tons) | Resources (% of world) | % Brine | % Pegmatite |
|---|---|---|---|---|---|---|
| Bolivia | - | - | 9,000,000 | 22.6% | 100% | 0% |
| Chile | 12,900 | 7,500,000 | 7,500,000 | 18.9% | 100% | 0% |
| Argentina | 2,900 | 850,000 | 6,500,000 | 16.3% | 100% | 0% |
| USA | 870 | 38,000 | 5,500,000 | 13.8% | 1% | 47% |
| China | 5,000 | 3,500,000 | 5,400,000 | 13.6% | 77% | 23% |
| Australia | 13,000 | 1,500,000 | 1,700,000 | 4.3% | 0% | 100% |
| Canada | - | - | 1,000,000 | 2.5% | 0% | 100% |
| DRC | - | - | 1,000,000 | 2.5% | 0% | 100% |
| Russia | - | - | 1,000,000 | 2.5% | 0% | 100% |
| Serbia | - | - | 1,000,000 | 2.5% | 0% | 100% |
| Brazil | 400 | 48,000 | 180,000 | 0.5% | 0% | 100% |
| Zimbabwe | 1,000 | 23,000 | - | - | - | - |
| Portugal | 570 | 60,000 | - | - | - | - |
| **Total** | **36,640** | **13,519,000** | **39,780,000** | **100%** | **68%** | **24%** |

*Source: Evans (2014); Jaksula (2015).*

*Notes: Total brine and pegmatite add to 92% of total resources as there are other lithium sources such as oil field brines, hectorite clays, and geothermal brine. Most of these other sources exist in the U.S., which is why the U.S. shares of brine and pegmatite add to only 48%.*

Resource-in-place estimates for lithium vary widely. One reason is the diversity of resource occurrences and the manner in which agencies and researchers gather data (Table 4). This study uses estimates by the U.S. Geological Survey.

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[7] We use USGS definition of reserves: "That part of the reserve base which 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. Reserves include only recoverable materials; thus, terms such as 'extractable reserves' and 'recoverable reserves' are redundant and are not a part of this classification system." Reserve Base: "That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the in-place demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently sub-economic (sub-economic resources)." Source: http://minerals.usgs.gov/minerals/pubs/mcs/2015/mcsapp2015.pdf.

[8] We use USGS definition of resources: "A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible." Source: http://minerals.usgs.gov/minerals/pubs/mcs/2015/mcsapp2015.pdf.

**Table 4. Variation in Lithium Resource Estimates**

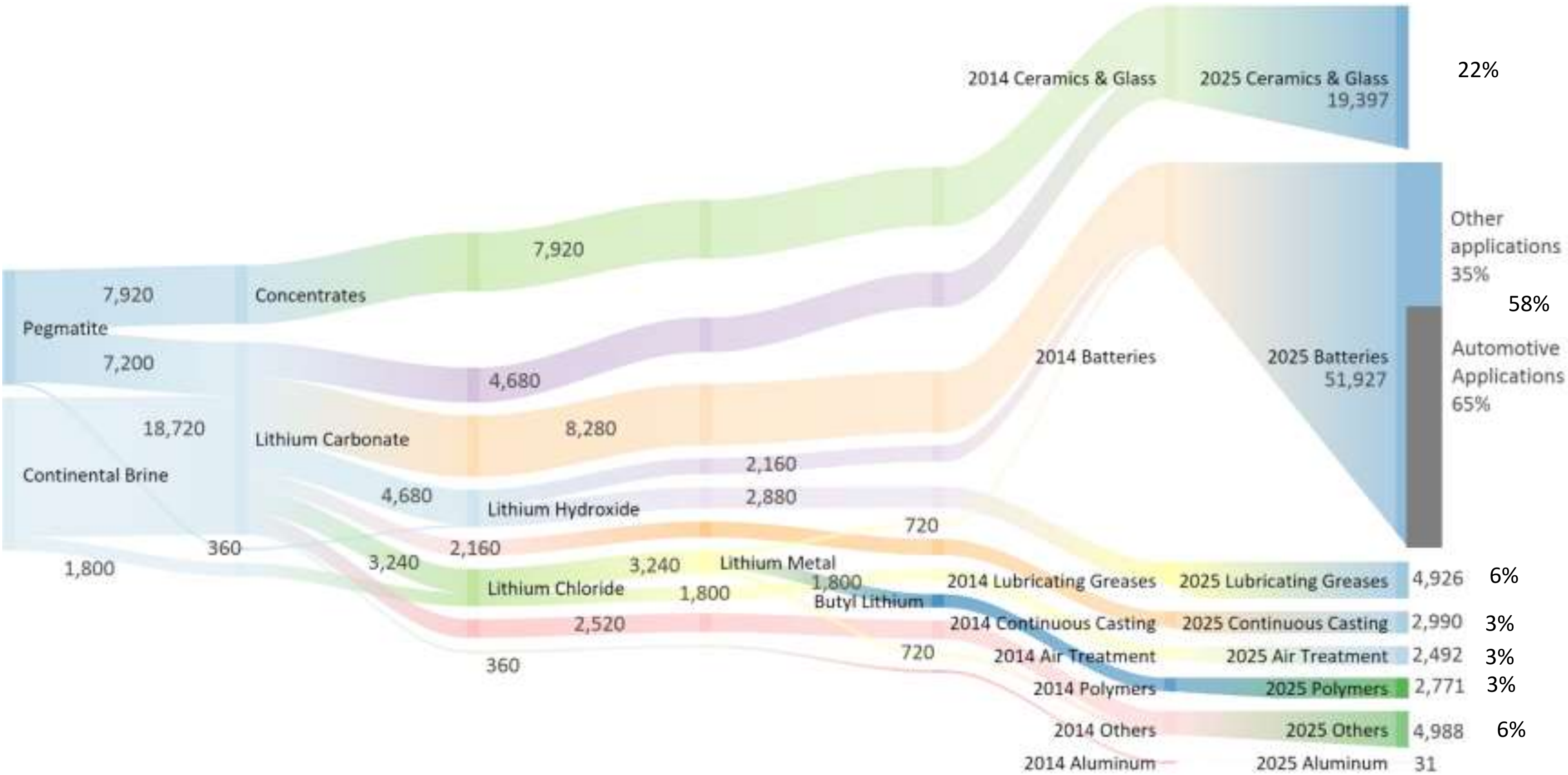
| Source | Resource (metric tons) |
|---|---|
| USGS (2015) | 39,780,000 |
| Mohr (2012) | 50,200,000 |
| Gruber (2011) | 38,775,700 |
| Yaksic (2009) | 63,341,900 |
| Evans (2008) | 28,459,100 |

Lithium is part of more than 200 chemical compounds. The flow diagram in Figure 13 reports lithium production data in 2014 and estimates in 2025 using the Base Case discussed. Pegmatite and brine sources produce most lithium compounds except lithium concentrates. Lithium carbonate is generally less expensive from brine sources than from pegmatite sources. The conventional process includes a series of evaporation ponds where lithium concentration increases in mined brine solution. For instance, initial lithium concentrations are about 0.15% in a mine in Atacama, Chile, and appreciate to about 6% after evaporation and processing. Following evaporation, the lithium solution goes through beneficiation and chemical processing to reach the desired product. The complete production cycle spans 8 to 12 months depending on evaporation conditions and magnesium content.

Battery grade lithium carbonate requires 99.5% pure lithium carbonate (Yaksic and Tilton, 2009; Peiro and others, 2013; Knight, 2014). Reports by Evans (2014), and Houston and Gunn (2011) state that brine recovery is lower at a rate of 60% to 70% depending on process efficiency. Evaporation is not the only method of lithium extraction from brine, as FMC has a proprietary method of extraction that is reportedly faster. POSCO, in joint venture with Lithium Americas, recently reported on a successful pilot project in Cauchari Salar, Argentina, demonstrating a 24-hour cycle and 90% lithium recovery (Lithium Americas, 2015).

Overall, there is a range of existing and evolving processes with different lithium recovery levels. The transition of evolving technologies into large-scale implementation will depend primarily on cost competitiveness.

**Figure 13. Lithium Flow from Source to End Use (metric tons)**




*The data and end use information for calculation of this lithium flow diagram is derived primarily from Deutsche Bank (2011), Yaksic and Tilton (2009), Gruber (2012), Peiro and others (2013), Evans (2014), Jaksula (2015), and from information published by major manufacturers like Albermarle Corporation and FMC (FMC Corporation, 2012).*

The primary demand for lithium concentrates are in the ceramics and glass industry, almost exclusively sourced from pegmatite occurrences. Spodumene is the most abundant type of pegmatite mineral containing lithium. Other pegmatite minerals include lepidolite, eucriptite and amnlygonite. Mining these hard rock mineral sources occur mostly in opencast drill and blast operations, followed by chemical processing with an overall recovery of about 80% to 87% (Evans, 2014).

The right side of Figure 13 presents the outlook of demand across different end applications based on the Base growth scenario. If battery applications grow at the forecasted rate (base case) by 2025, this will consume about 58% of lithium, much higher than any other end use. Batteries consume primarily lithium carbonate and lithium hydroxide. In a valuation of cathode components in 2025, Deutsche Bank (2011) estimates the distribution of batteries between the automotive sector (65%) and consumer applications (35%).

With the projected growth in demand for lithium understood (Base case), the supply side may be evaluated. An investigation of historical lithium production rates explore if existing production capacity may be increased. As shown in Figure 14, the lithium industry responded with an almost six-fold production increase over the past two decades. The most significant increase in capacity (around 75%) occurred in 1996, when production in South America began using cheaper brine sources. The industry cut back production during the economic downturn in 2008 and 2009 indicating sensitivity of lithium demand to changing market conditions. In 2010, annual production rose by 49%, owing to increasing output from facilities underutilized during the recession.

**Figure 14. Historical Lithium Annual Production Rate**

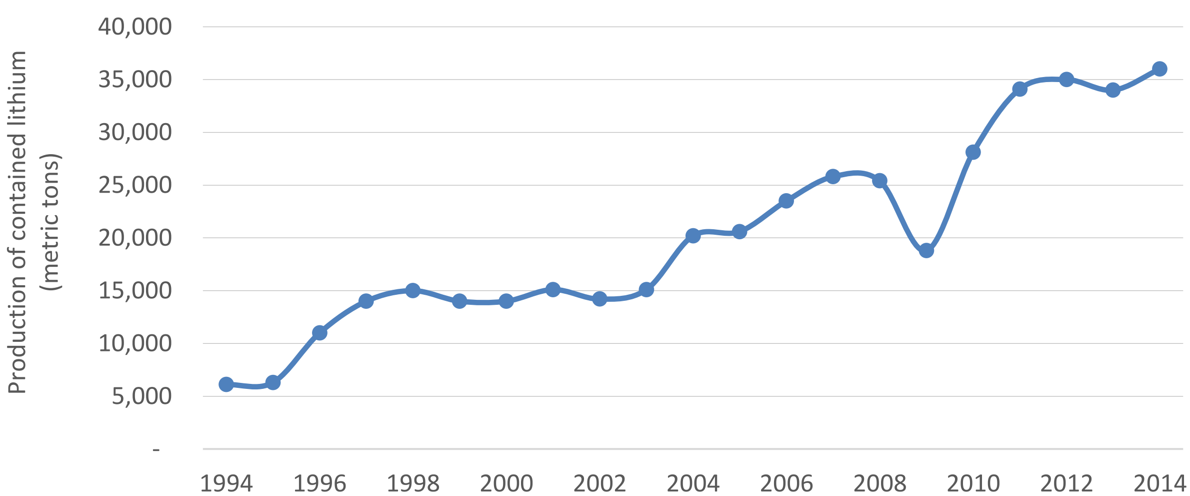



Table 5 lists production capacities of companies that contributed 95% of global production in 2014. The data comes from various published sources such as manufacturers and market news. The weighted extractive capacity utilization globally is 55%, with China having the most under-utilized facilities. Estimating maximum achievable utilization is not feasible given the significant diversity in individual processes of extraction and beneficiation, as well as government regulations. Whether and how much utilization can be increased at existing extraction sites would require better information on resource quality, extraction process and associated costs, and other variables. This remains an area for further research.

**Table 5. Utilization of Lithium Production Facilities**

| Country | Capacity in place (metric tons of LCE) | Production in 2014 (metric tons of LCE) | Utilization |
|---|---|---|---|
| Chile | 101,875 | 68,499 | 67% |
| Argentina | 23,000 | 15,399 | 67% |
| Australia | 120,000 | 69,030 | 58% |
| Brazil | 2,300 | 2,124 | 92% |
| China | 80,750 | 26,550 | 33% |

*Note: One ton of lithium = 5.31 tons of lithium carbonate equivalent (LCE).*

Aside from increasing utilization rates of existing capacity, new projects can supply growth in production. In recent years, there has been huge interest in traditional and new types of resources. Table 6 lists all expected and known capacity additions and the companies leading the projects. All of these projects except that of Rio Tinto have a target start date earlier than 2020. These projects' potential volumes when added to 2014 capacity (Table 2) provide an estimate of global production nearing 538,000 metric tons of LCE. This proposed capacity requires traditional brine and pegmatite sources to come online.

**Table 6. New Lithium Production Projects**

| Country | Company | Project | Type of source | Annual LCE Production Capacity |
|---|---|---|---|---|
| Bolivia | Comibol | Salar de Uyuni | Continental brine | 30,000 |
| Argentina | Galaxy Resources Ltd | Sal de Vide | Continental brine | 25,000 |
| Chile | Albermarle | La Negra | Continental brine | 20,000 |
| Argentina | Lithium Americas | Cauchari-olaroz project | Continental brine | 20,000 |
| Argentina | Orocobre | Olaroz lithium plant | Continental brine | 17,500 |
| Argentina | Rodonia | Salar de Diablillos | Continental brine | 15,000 |
| USA | Simbol | Salton Sea | Geothermal Brine | 16,000 |
| Mexico | Bacanora Minerals Ltd | Sonora lithium project | Hectorite clay | 35,000 |
| USA | Western Lithium | Kings valley (Humboldt county, Nevada) | Hectorite clay | 26,000 |
| USA | Albermarle | Arkansas | Oilfeild Brine | 20,000 |
| Canada | Nemanska Lithium Inc | James Bay (Wahbouchi lithium mining project) | Pegmatite | 43,684 |
| Australia | Reed Resources | Mount Marion | Pegmatite | 25,276 |
| Australia | Altura | Pilgangoora Lithium | Pegmatite | 19,000 |
| Finland | Kliber Oy | Ostrobothnia | Pegmatite | 4,000 |
| Canada | Nemanska Lithium Inc | James Bay (Wahbouchi lithium mining project) | Pegmatite | 3,277 |
| **Total** | | | | **319,737** |

Among new types of resources, Western Lithium and Bacanora Minerals Limited have projects in *hectorite clay* in USA and Mexico respectively; Albermarle will employ a lithium production plan from *oil field brine* in Arkansas, USA, while Simbol Materials uses *geothermal brine* in California, USA, and Rio Tinto uses *Jadarite* in Serbia. In traditional pegmatite and continental brine sources, Galaxy Resources, Orocobre Ltd, Lithium Americas, Nemanska Lithium are new market entrants. It is uncertain if these potential sources will provide results. Global capacity could reach 599,000 metric tons of LCE by including hectorite clay projects, and 665,000 metric tons including oil field and geothermal brines.

It may be possible to achieve a potential range of 538,000 to 665,000 metric tons by 2020. By comparison, Evans (2014) estimates a possible range of 593,000 to 640,000 metric tons of LCE for 2020. Capacity additions covered in this report include most of the projects announced publicly. Additional projects under consideration or development may yet to be announced. Some project initiations may be delayed subject to market conditions and company finances, or may be abandoned if mine locations are more costly than anticipated, and others may prove to be non-commercial if lithium concentration is not high enough. For example, Galaxy Resources closed a mine in Mount Cattlin in 2012, and RB Energy suspended a lithium carbonate plant at Quebec in 2014 (Morris 2015).

Figure 15 shows location, quantity and cost of production from new capacity sources. Continental brine is the preferred resource for expected new capacity because of relatively low extraction cost of more highly concentrated lithium. Lithium is more expensive to extract from pegmatite sources. New types of sources might contribute significant future capacity, but the market price of lithium (approximately $6,000 per ton for battery-grade lithium carbonate) will highly influence the feasibility of higher cost projects. Most new projects are located in North and South America, where the risks and uncertainty associated with regions like Bolivia and Chile will play an important role for capacity development and supply chain integrity.

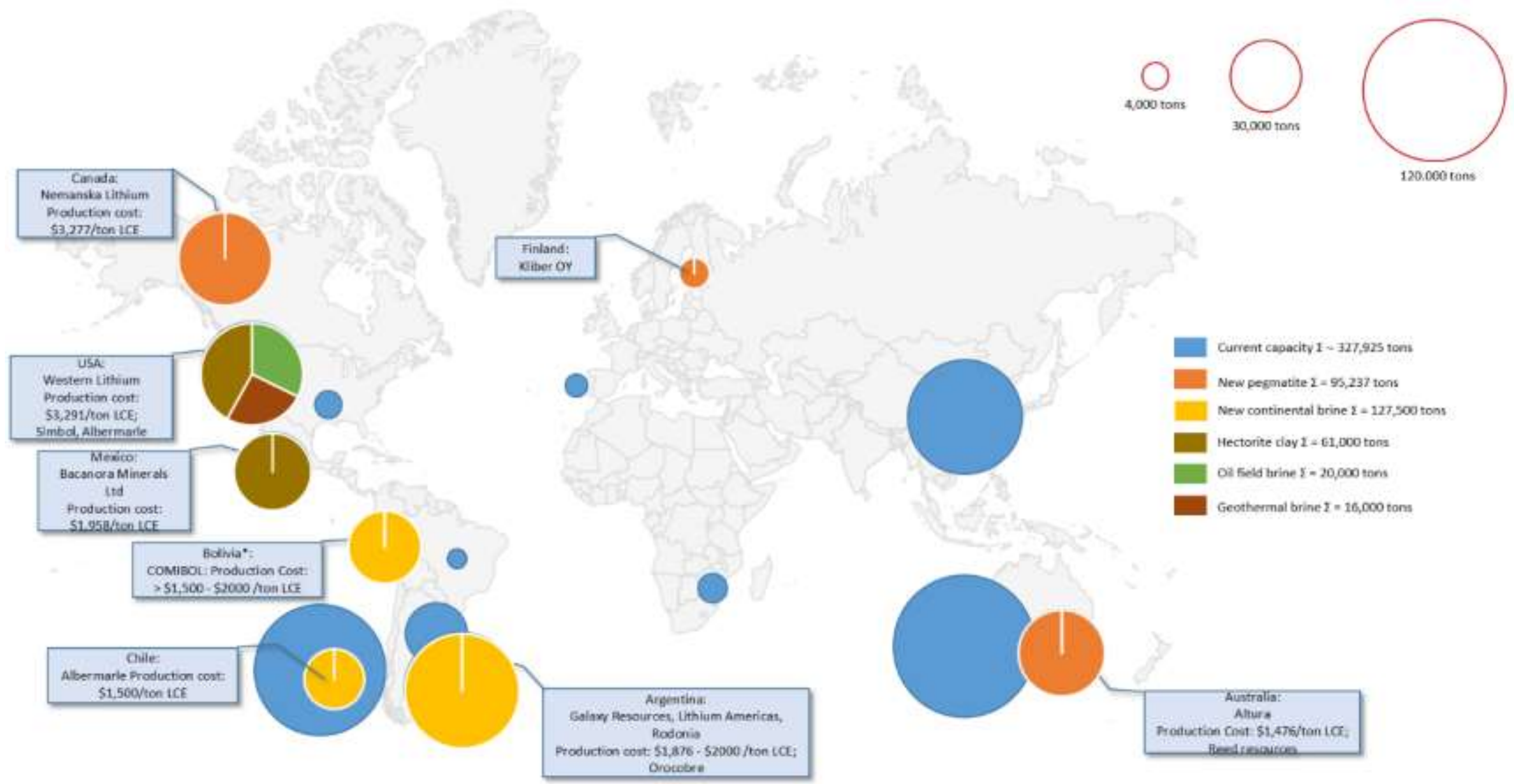
Like other extractive industries, the lithium industry may face serious challenges in the future. Access to lithium sources that bear a high enough concentration may prove difficult to justify large capital investments. Bolivia, which holds the largest and richest lithium resource, poses considerable political risk. Worldwide, Bolivia ranks 77th among fragile states (Fund for Peace, 2015). The Human Development Index for Bolivia, 113th worldwide, is among the lowest in South America (United Nations Development Program, 2014). Transparency International also ranks Bolivia 103rd in the world in corruption perception index (Transparency International, 2014).

Rapid scale up in mining capacity just like any industrial endeavor can create environmental problems without adequate protections. In April 2015, the Bolivian government announced an open bid for rights to assist in developing a large processing plant.[9] In the region of Bolivia's vast Salar de Uyuni salt flat, the location of Bolivia's premium lithium resources, 46% of the local agrarian population of about 10,000 uses limited ground water for irrigation. Lithium mining in the region could exert stress on water supply. Landscape changes with mining could affect tourism that employs 26% of the local population (Fernandez-Aguilar, R. 2009; Romero, 2009; Rüttinger and Feil, 2010).

The Chilean government, which hosts the largest production of lithium, expressed interest in launching a state mining company, changing legal framework, and increasing royalties on current and future leases (Comision Nacional del Litio, 2015). This adds uncertainty to the outlook for Chilean lithium mining as the private producers might limit or delay new investments until the new framework is established and the Chilean government addresses their concerns.

[9] See http://www.dw.com/en/bolivia-to-supply-lithium-for-e-car-batteries/a-18416014.

**Figure 15. Location and Cost of Production of New Lithium Extraction Facilities**




All capacity data is in metric tons (ton) of lithium carbonate equivalent (LCE).
Production costs reported here are as announced by respective companies. *Cost used as reported by Yaksic (2008), due to unavailability from company data
Current capacity includes both pegmatite and brine sources

**Figure 16. 2014 Lithium Production Capacity Estimate by Company**

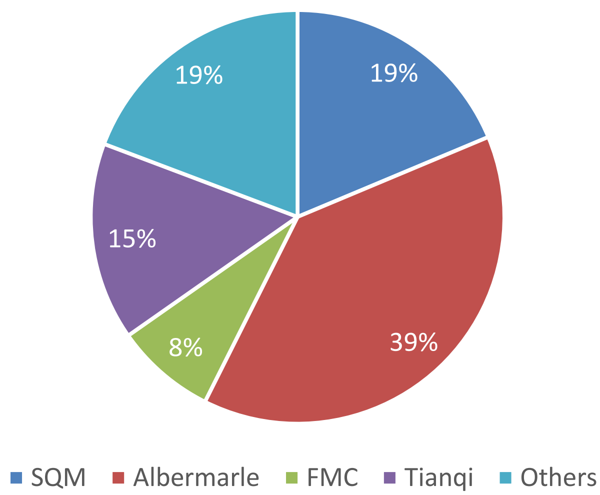



Figure 16 shows that four companies control more than 80% of world's lithium production.[10] Observations by Maxwell (2015) suggest that the lithium market is becoming more competitive with new entrants (implicit in Table 6). This is a positive sign if mergers and acquisitions in future do not reverse the situation. Lithium America and Western Lithium announced a merger in June 2015 (Western Lithium, 2015). There are reports that Simbol Materials also is seeking an acquisition (Richard, 2015).

## *Cobalt*

Cobalt production, unlike lithium, is a by-product of copper and nickel mining. In 2012, 66% of global cobalt came from copper outputs, 31% from nickel, while only 3% from independent mining (Roberts and Gunn, 2014; Minor Metals Trade Association, 2015). Another aspect that differentiates cobalt from lithium is its refining location. Ore from cobalt mines moves to refineries for production of refined cobalt, and these refineries oftentimes are geographically separate. Table 7 presents cobalt mine and refinery production in 2012.

The Democratic Republic of Congo (DRC), one of the largest copper producers in the world, is the largest producer of cobalt (U.S. Geological Survey, 2015).[11] The DRC produces 49% of the world's cobalt ore but produces only 4% of refined cobalt. China is a major importer of cobalt from the DRC and other locations and produces 38% of the global refined cobalt. Countries like Belgium and Japan, which do not have any significant ore production, also produce refined cobalt. Estimates of cobalt reserves worldwide are about 7.2 million metric tons with total terrestrial resources of 25 million metric tons. About 120 million tons of cobalt deposits are in ocean-floor manganese nodules in the Atlantic, Indian and Pacific Oceans. New mine production is not the only source of cobalt supply; in 2014, recycled scrap contained 27% of cobalt consumption (U.S. Geological Survey, 2015).

Utilization is important to consider the industry's ability to ramp up production. Table 7 shows a global weighted average utilization[12] of 58% of total refining capacity. The high utilization rates of Finland and Canada suggest that there could be significant potential for improvement in other locations as well,

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[10] Production of Talison Lithium is counted 49% in Albermarle and 51% in Tianqi, as per their respective share in the company.
[11] Chilean copper deposits, which are the largest in the world, are not known to contain cobalt.
[12] The Belgium utilization shown in Table 7 looks extraordinary because Belgium's production involves production from refineries located in China but owned by the same Belgian company; this production was not included for China (Shedd, 2015).

because of similarities in process technology and raw material. As in the case of lithium, achievement of higher utilization rates depend upon quality of resource base, potential for efficiency gains at facilities, which depend on production processes and refining technologies as well as ownership and regulations. Also like lithium, new production sources will play a significant role in future supply.

**Table 7. Cobalt Production, Refining and Utilization**

| Country | Mine Production (metric tons) | Share of Global Production | Refinery Production (metric tons) | Share of Global Refining | Refinery Capacity (metric tons) | Utilization |
|---|---|---|---|---|---|---|
| Congo | 51,000 | 49% | 3,021 | 4% | 12400 | 24% |
| China | 7,000 | 7% | 29,800 | 38% | 50000 | 60% |
| Canada | 6,625 | 6% | 5,981 | 8% | 6420 | 93% |
| Russia | 6,300 | 6% | 2,186 | 3% | 6000 | 36% |
| Australia | 5,882 | 6% | 4,860 | 6% | 6700 | 73% |
| Cuba | 4,900 | 5% | - | 0% | | - |
| Zambia | 4,200 | 4% | 5,665 | 7% | 8800 | 64% |
| Brazil | 3,900 | 4% | 1,750 | 2% | 3000 | 58% |
| New Caledonia | 2,620 | 3% | - | 0% | 0 | - |
| Philippines | 2,600 | 3% | - | 0% | 0 | - |
| South Africa | 2,500 | 2% | 1,102 | 1% | 1400 | 79% |
| Morocco | 1,800 | 2% | 1,314 | 2% | 2000 | 66% |
| Indonesia | 1,700 | 2% | - | 0% | | 0% |
| Finland | 635 | 1% | 10,562 | 14% | 13000 | 81% |
| Madagascar | 630 | 1% | 493 | 1% | 5600 | 9% |
| Papua New Guinea | 469 | 0% | - | 0% | 0 | - |
| Botswana | 195 | 0% | - | 0% | 0 | - |
| Zimbabwe | 88 | 0% | - | 0% | 0 | - |
| Belgium | - | 0% | 4,200 | 5% | 1500 | 280% |
| France | - | 0% | 326 | 0% | 500 | 65% |
| India | - | 0% | 800 | 1% | 2060 | 39% |
| Japan | - | 0% | 2,542 | 3% | 2600 | 98% |
| Norway | - | 0% | 2,969 | 4% | 5200 | 57% |
| Uganda | - | 0% | 374 | 0% | 720 | 52% |
| **Total** | **103,044** | **100%** | **77,945** | **100%** | **127,900** | **61%** |

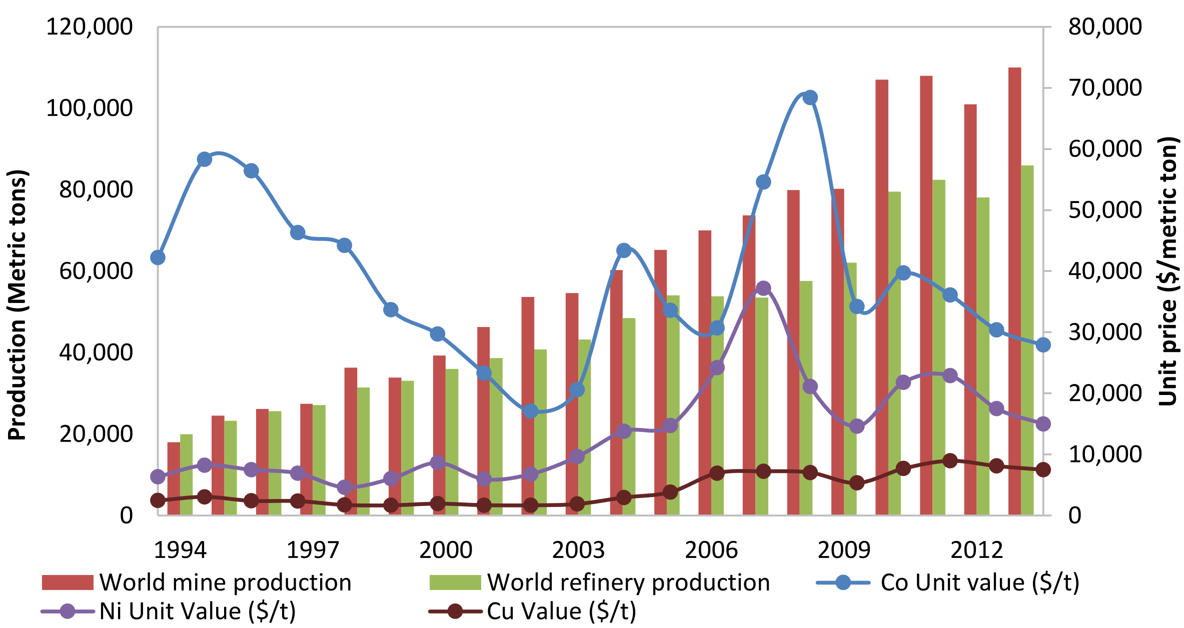
The cobalt industry is a target for major investments in new projects as summarized in Table 8. There are projections of an additional 65,955 tons of cobalt mining capacity and 54,230 tons of refining capacity globally by 2017. USGS (2015) confirms refinery capacity increased by 2,100 metric tons at the end of 2013. Almost 25% of total new refining capacity may happen in the DRC, which would increase the largest ore producer's share in refined cobalt; but confirmation of the status of these projects is yet to come.

The challenges associated with cobalt supply are greater than most metals like iron or aluminum. A large number of end-use applications, shown in Figure 8 have a high dependence on cobalt, making cobalt a critical metal as designated by the National Research Council (2008). Given that production from DRC accounts for almost half of global production, the unstable history of that country is a major concern. Figure 17 shows historical price volatility, much of it attributed to political instability and market manipulation (Alonso and others, 2007). For example, DRC banned in July 2013 all export of cobalt concentrates. More recently, a shortage of domestic electricity to refine the restricted exports domestically forced the country to increase the export duty on cobalt concentrate by 66% to $100 per metric ton (London Metal Exchange, 2015). In recent years, the gap has grown between mine production and refinery output, an indication of stockpiling. Locations of stockpiles and extent of inventory build will require careful analysis to account for the extensive international trade of cobalt ore and supply-demand balances.

**Table 8. New Cobalt Ore and Refinery Expected Capacity Additions (metric tons)**

| Country | 2013 | 2014 | 2015 | 2016 | 2017 | 2013-2017 |
|---|---|---|---|---|---|---|
| | | | **ORE** | | | |
| Australia | 250 | | 2,700 | 3,000 | | 5,950 |
| Cameroon | | | | 6,100 | | 6,100 |
| Canada | 425 | | 1,575 | 230 | | 2,230 |
| Congo | 37,000 | 4,500 | | | | 41,500 |
| Indonesia | | | | | 2,200 | 2,200 |
| Mexico | | 2,400 | | | | 2,400 |
| Philippines | | 1,730 | | 645 | | 2,375 |
| Vietnam | 200 | | | | | 200 |
| **Total** | **37,875** | **8,630** | **4,275** | **9,975** | **2,200** | **62,955** |
| | | | **REFINERY** | | | |
| Australia | | | 2,700 | 3,000 | | 5,700 |
| Cameroon | | | | 6,100 | | 6,100 |
| Canada | 2,500 | | 1,575 | | | 4,075 |
| Congo | | 4,500 | 10,000 | | | 14,500 |
| Japan | 4,500 | | | | | 4,500 |
| Mexico | | 2,400 | | | | 2,400 |
| Russia | | | 3,000 | | | 3,000 |
| Philippines | 2,600 | 1,730 | | | | 4,330 |
| USA | | 1,925 | | | | 1,925 |
| Zambia | | 7,700 | | | | 7,700 |
| **Total** | **9,600** | **18,255** | **17,275** | **9,100** | **-** | **54,230** |

**Figure 17. Cobalt Historical Trends**

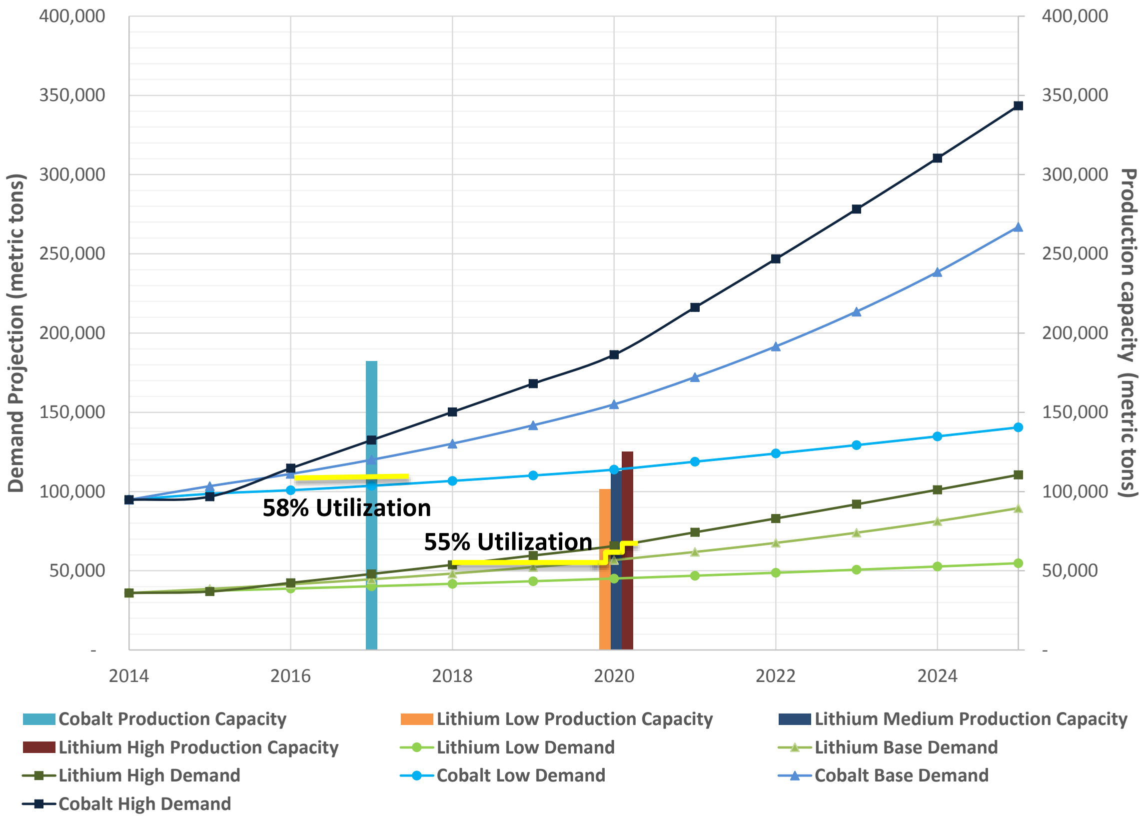



*Source: U.S. Geological Survey (2013)*

## BALANCE OF DEMAND AND SUPPLY PROJECTIONS

In Figure 18, vertical columns represent nameplate production capacity in 2017 for refined cobalt and in 2020 for lithium using publicly available data. Three scenarios are represented for lithium production capacity in 2020 to account for uncertainty associated with project realizations. The data on cobalt is more uncertain; hence, the sole estimate for 2017. Yellow lines represent a conservative interpretation of historical utilization rates, 58% for cobalt and 55% for lithium mines.

**Figure 18. Lithium and Cobalt Projected Mine-Design Capacity and Capacity Utilization versus Projected Demand**




*Note: Lithium low production capacity = pegmatite + brine. Lithium medium production capacity = pegmatite + brine + hectorite clay. Lithium high production capacity = pegmatite + brine + hectorite clay + oil field brine + geothermal brine.*

Mine design capacity for cobalt production will exceed demand in 2017, but if the utilization continues to be at the current weighted average level of 58% (roughly 105,000 metric tons) production will fall short of demand in 2017 in almost all three cobalt-demand scenarios. Presumably, the low utilization rate resulted from the weakness of the market since the 2008-09 crises and it is likely that at least some of these facilities will be able to increase their production if the demand for cobalt strengthens. For example, roughly 75% utilization in 2017 should suffice to meet even the high demand for cobalt. However, by the end of the decade, new production capacity must exist in the high-demand case, and in the early 2020s in the base-demand case. Current slow growth of global economy implies that cobalt demand growth might be much lower, where existing capacity with an increase in utilization to about 75% should suffice until 2025.

At the current weighted average utilization of lithium production capacity of about 55%, the projected capacity from continental brine and pegmatite sources alone (Figure 16, low-case orange bar) falls short of base- and high-demand scenarios. If hectorite projects materialize (Figure 16, medium-case dark-blue bar), then both low- and base-demand scenarios for lithium can be fulfilled. If all new projects come online including those from geothermal brine and oil-field brine (Figure 16, high-case brown bar), then 55% utilization will be sufficient to cover all demand scenarios for lithium in 2020. However, to meet year 2025 high-demand of roughly 110,000 tons, the utilization rate needs to reach almost 90% (Figure 16, brown bar). This goal is challenging given past performance. Numerous caveats such as the uncertainty around production cost and production yield exist with new, untested sources of lithium capture like geothermal brines and hectorite clay.

## CONCLUSION

Our analysis indicates that 75% utilization rates at existing production capacity coupled with upcoming projects can satisfy most of the expected demand for both lithium and cobalt in the short run. However, high-growth scenarios require new capacity and/or significantly higher rates of utilization in existing facilities. The influence of geopolitical risks, growth in other applications, and development of new applications could push demand in excess of production capacity.

Government regulations in response to local interests, environmental concerns and future sustainability have influenced material supply in the past and may continue. Extrapolating the high-demand scenario for lithium to 2050, the automotive sector would consume 4 to 5 million tons of lithium cumulatively. Including all other sectors, 6 to 7 million tons of total consumption would represent 45 to 52% of known global reserves and 15-17% of known resource-in-place as estimated by the USGS. Price changes drive conversion from resource to reserve and different applications have unique capacities to absorb price increases.

As shown in Table 1, lithium represents a small percentage of materials mass in batteries. As such, even a five-fold increase in lithium price may not significantly affect battery-pack price (Grosjean and other, 2012). However, if the cost of manufacturing batteries declines significantly while the price of lithium increases due to escalated demand, lithium's significance battery cost may rise. Nykvist and Nilsson (2015) report the cost of manufacturing batteries for electric vehicles dropped from $1000/kWh to $410/kWh between 2007 and 2014. Further, Nykvist and Nilsson (2015) report that the market leaders in electric vehicle battery production lowered costs to $300/kWh in 2015 with an expectation that the cost may decline by 8% annually in the near future. According to Atacama (2016), the cost of battery-grade lithium carbonate doubled to $13,000 per metric ton in the last two months of 2015. With these numbers, the share of lithium can be as high as 6% in the total cost of a battery.[13] In recent media articles, General Motors claims a battery costs $145/kWh, elevating the lithium share as high as 12% of the total battery cost (Cobb, 2015). The quantity of lithium used for manufacturing a single LIB has not reduced while its price has almost doubled. Therefore, even as declining costs of other manufacturing processes drive the total cost of batteries down, the share of lithium can be a significant and critical component of LIBs in the future.

One supply response to lithium price appreciation is recycling (Gaines, 2014). Currently the lithium recovery rate is only 1% globally from all applications (Graedel and others, 2011), but technologies to extract lithium from lithium-ion batteries are being recycled commercially by companies like Accure technology, Akkuser, Batrec Industrie, Toxco, Umicore and Recupyl. Policy directives encourage recycling such as *Directive 2006/66/EC* by the European parliament requiring battery accumulation and

[13] Assuming 0.25 kg of lithium per kWh in NCA chemistry (Simon, 2015); $13,000 per metric of lithium carbonate; Battery size: 60 kWh NCA (Tesla model S) (Fehrenbacher, 2015)

recovery rates to exceed 50%.[14] A risk faced by the recycling industry is the assumption that cobalt content will be low in future battery chemistries. Cobalt is the most valuable metal recycled from batteries today. Second use of spent lithium-ion vehicle batteries for grid-energy storage is another option and may be feasible (Heymans and others, 2014). While many factors could ease pressure for new production capacity, development of new applications like grid-energy storage and use of lithium-ion batteries in heavy vehicles have the potential to significantly increase demand beyond what is typically expected in the literature.

Lithium-ion batteries gained new momentum in recent years, and lithium production expanded during the past decade. The battery and extractive industries show potential to change status quo of energy storage, while facing unique challenges. Technological advancements in LIB performance and reduction in battery manufacturing costs are the most crucial factors to which the extractive industries for both lithium and cobalt will have to respond (Goodenough, 2013).

Our research premise was that demand for battery materials would hinge on battery chemistry driven by applications, within a context of extractive industry dynamics. A history of high volatility in cobalt prices and dependency on the DRC and Zambia for more than 50% of global production prompted a shift towards reduction of cobalt use. The LCO battery chemistry traditionally has been the most common technology in consumer-IT applications, but geopolitical sensitivity around cobalt may hobble its future adoption in larger applications such as vehicles and grid-based energy storage. The lower safety performance of LCO batteries further adds momentum to the shift toward NMC and NCA chemistries (The Boston Consulting Group, 2010; Deutsche Bank, 2011; Dunn, 2011). Lithium is what gives lithium-ion batteries superior properties to other battery types due to its favorable density, battery size, electrochemical, and other properties. Lithium will continue to be a crucial component of batteries, but battery end-uses may shift as the tolerance to different conditions affects energy storage materials strategies.

[14] See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:266:0001:0014:EN:PDF as published by the European parliament and the Council of the European Union (2006).

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