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Lithium and cobalt – a tale of two commodities

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Executive summary

The electric vehicle (EV) revolution is ushering in a golden age for battery raw materials, best reflected by a dramatic increase in price for two key battery commodities – lithium and cobalt – over the past 24 months. In addition, the growing need for energy storage, e-bikes, electrification of tools, and other battery-intense applications is further increasing the interest in these commodities. However, the recent concerns regarding the future of the raw material supply availability for batteries and the impact of rising commodity prices on battery production costs have highlighted risks that may create divergent futures for these two commodities. The strategic response needed will likely differ across industry players such as automotive OEMs, battery manufacturers, mining and refining companies, and financial investors; for all players there is a growing imperative to understand the complexities and dynamics of this rapidly changing market and to ensure that their strategies are robust in the face of future uncertainties.

Both the lithium and cobalt markets have historically been driven by battery demand – primarily from consumer electronics – representing 40 percent and 25 percent of demand respectively in 2017. However, the growing adoption of EVs and need for EV batteries with higher energy densities will see the demand for lithium increase more than threefold from 214 kt to 669 kt LCE[1] between 2017 and 2025, whereas cobalt will increase by 60 percent from 136 kt to 222 kt over the same period in McKinsey's base case outlook. This forecast assumes that Li-ion battery technologies will be the prevalent battery technology for the foreseeable future.

Recent price spikes for lithium and cobalt have raised concerns regarding the long-term supply availability of these commodities and highlighted the very different supply side dynamics for both. Over 95 percent of the world's lithium supply occurs as a primary product in the form of brines or hard rock ores, with a global production footprint including Latin America, Australia, and China. Conversely, less than 10 percent of cobalt supply occurs as a primary product, with the remainder produced as a by-product of primarily copper and nickel mines and over 65 percent of global production concentrated in the Democratic Republic of Congo (DRC). These price spikes have seen a swathe of expansion announcements for lithium over the next several years, suggesting ample capacity to meet the growth in demand to 669 kt LCE by 2025. However, there is much more concern for cobalt given the lack of transparency in the value chain and DRC country risk.

How and if these commodities diverge will depend on several factors, the most significant being the speed of EV adoption and the shift in EV battery chemistries across geographies. Whatever future emerges, industry players will need to base their strategic responses on a sound understanding of the future supply and demand dynamics, battery technology evolution, pricing, and risk management mechanisms.

The following base case analysis is based on a set of assumptions regarding the global EV demand growth and battery chemistries the industry will adopt. Although we believe these assumptions to have a high likelihood of occuring, how the industry evolves will be affected by government policies (especially in the DRC), battery technology innovations, and industry economics. Any major changes in these areas may result in a vastly different outlook from what is presented here.

1 Lithium carbonate equivalent, which is the industry standard for measuring lithium volumes

Back to the future … with a twist

Over one hundred years ago electric cars were a common sight on the city streets of Europe and the United States. An American – Thomas Davenport – is credited with building the first electric vehicle (EV) in 1835, and by 1900 EVs were so popular that New York had a fleet of electric taxis and electric cars representing one third of all vehicles on the road (indeed, it was claimed the Fritchle electric car could travel 100 miles on a single charge). When Henry Ford introduced the mass-produced and gas-powered Model T in 1908 it symbolized the end of the age of the electric car until its recent revival. This technological "rediscovery" is already having a revolutionary impact on the automotive industry ecosystem as players scramble to revise business strategies, develop new technologies, and reconfigure global supply chains and manufacturing footprints while trying to secure access to battery raw materials.

Two of the main commodities that have been direct beneficiaries of the EV revolution are lithium and cobalt (for the impact on nickel see our publication in November 2017, The future of nickel: A class act) whose periodic symbols – Li and Co – have been included in investor presentations and conferences with increasing frequency over the past 24 months as their respective prices have edged steadily higher. Historically, demand for these two commodities was driven by multiple end sectors, although battery demand has been increasing its share. In 2010, the breakdown of the 123 kt of LCE demand approximated to: ceramics/glass 42 percent, batteries (rechargeable and non-rechargeable primarily for portable electronics) 14 percent, and lubricating greases 11 percent. By 2017 batteries had increased its share of the 214 kt of LCE demand to 41 percent with ceramics/glass only accounting for 23 percent. A similar story, but to a lesser extent, occurred for cobalt when in 2010 the end sector split for the 71 kt of refined equivalent cobalt demand approximated to: 25 percent batteries, 23 percent super alloys, 17 percent tools and hard materials. By 2017 batteries had increased its share of the 136 kt of refined equivalent cobalt apparent demand[2] to 30 percent. In both cases, the growth in EV battery demand – particularly in China – had been key to driving overall demand growth.

Aside from the significant growth in demand for rechargeable batteries due to the EV revolution – discussed further below – increasing vehicle battery sizes and increased raw material intensities present additional strong tailwinds for lithium and cobalt demand. For example, today's typical EV passenger vehicle with a NMC622 cathode 55kWh battery pack will contain 7.4 kg LCE and 12 kg refined Co; in the future, a similar car with a 77 kWh battery pack equipped with a NMC811 cathode will contain 8.4 kg LCE and 6.6 kg refined Co.

THE EV REVOLUTION

The underlying driver for both lithium and cobalt demand is the EV revolution, which is gathering pace. The latest estimates from McKinsey's Future Mobility Initiative suggests that global EV production will increase from 3.2 million units in 2017 to 13 to 18 million units by 2025 ultimately reaching 26 to 36 million units in 2030. There are several drivers that will impact the extent and speed of global EV adoption, including government regulations and targets, future battery costs, the availability of EV charging and servicing infrastructure, OEMs' automotive platform choices, and consumer preferences.

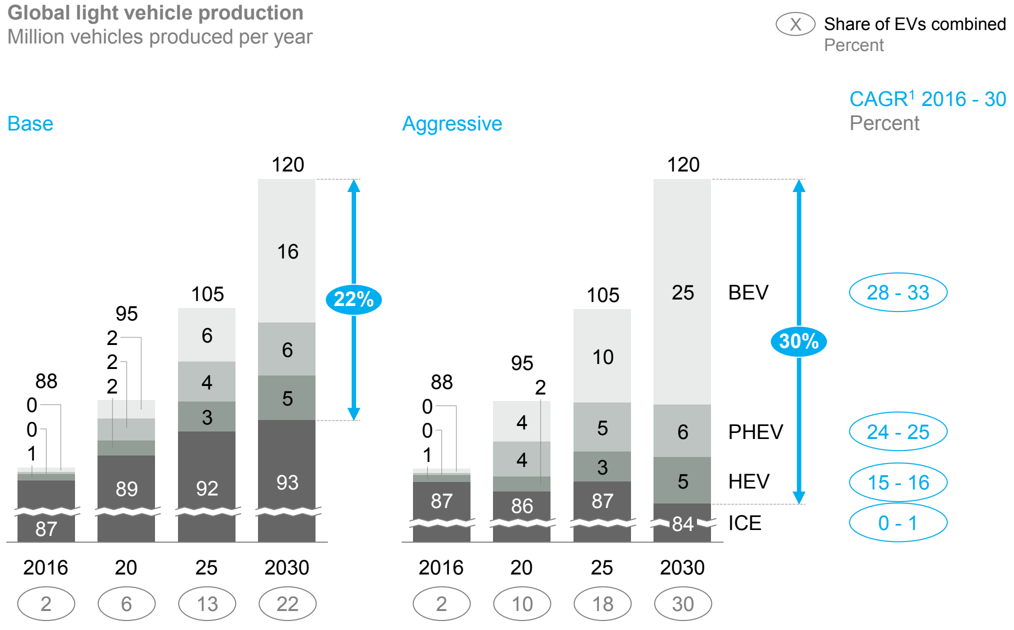
2 Apparent demand includes the contribution of stockpiling of refined product, either by private companies (e.g., Cobalt -27 which has ~3 kt of inventories) or by countries as part of a strategic stockpiling policy (e.g., between 2015 and 2017, China's State Reserve Bureau is believed to have purchased cobalt for its stockpile, estimated at ~5 kt per year)

While North America and Europe are important, the major development of the EV revolution will be determined by Chinese consumers and actions taken by China's government. Depending on the scenario, we expect China to account for 50 to 60 percent of EVs in 2030.

Exhibit 1

Growth in EVs from 2010 to 2025 split by hybrid and pure electric

Global light vehicle production
Million vehicles produced per year



1 Range of base and aggressive scenarios
SOURCE: McKinsey Sustainable Mobility Initiative

Regulations. Governments are increasingly using regulatory targets combined with incentives for switching to renewables to encourage consumers to make the change to EVs. China has been a leader, pushing for a 20 percent EV target adoption by 2020 and recently introducing a change in subsidies from the 2017 levels. Starting in 2018, only EVs with a 300 km or greater range will retain the prior subsidies. Vehicles with a 400 km or greater range will see an increase in subsidies, while those with a range under 150 km will get no subsidies at all. In 2017, many EU countries seemed to leapfrog China's ambitions by announcing goals to move entirely to EVs by the 2030 to 2040 timeframe.

Battery costs. Significant reductions in battery production costs have encouraged EV adoption. These reductions are due to larger, more efficient battery manufacturing facilities, e.g., Tesla's Gigafactory, and new battery design optimizing energy densities and cost per kilometer travelled. Battery costs have decreased from ~USD 1,000/kWh in 2010 to USD 230/kWh by 2017. Today, some of the best in class batteries have costs less than USD 150/kWh. McKinsey's Center for Future Mobility estimates that at ~USD 100/kWh batteries will reach a tipping point at which EVs will be cheaper than ICE cars. However, it is unlikely that this point will be reached before 2025[3].

EV infrastructure. Currently two of the main reasons deterring customers from buying EVs are concerns about running out of power on the road and long charge times. Although some federal and municipal governments have pledged to build charging stations, the scale of the current infrastructure investment lags what is available for gasoline powered cars,

3 Commodity prices and the type of battery chemistry will have a significant impact on how quickly this cost is reached

e.g., in the US there are 115,000 gas stations versus 17,000 EV charging stations. Automotive OEMs are also investing aggressively, for example, Tesla plans to build 8,500 rapid-charging stations globally by 2019, with 1,130 being "supercharger" stations with faster charging times. However, even greater levels of investment are still required to reassure the customer.

OEM strategies. OEMs are increasingly focusing on EV product ranges, with over 350 new EV models planned to be launched over the next several years. For example, Volkswagen is aiming to leapfrog industry leader Tesla by 2025 by redirecting its efforts from diesel cars to EVs; BMW reached its goal of selling 100,000 plug-in vehicles in 2017 and wants to have 25 EV models by 2025. General Motors is expanding its EV roster, and has a goal of selling 1 million units by 2026 and Toyota has the same goal by 2030. This new "space race" between automotive OEMs to provide the EV vehicle of the future bodes well for the EV revolution.

Consumer preferences. The vagaries of consumer preferences will also play an important role in the speed of EV adoption. Public acceptance of the new technology will be affected by everything from environmental concerns, car design, prices, and the range of EV models to the features available for those models. According to McKinsey's 2016 EV Consumer Survey, the top two reasons consumers cite for not buying an EV are high prices and the limited driving range on a single charge. Increased battery densities have contributed to considerable progress on the latter point, extending driving range from below 200 km to more than 400 km. Furthermore, EVs are now seen as status symbol from a consumer perspective primarily due to Tesla's efforts. More than any other EV, Tesla has switched the conversation from "tree hugger" cars to "the coolest car anyone could own."

While we expect passenger vehicles to be the main driver of battery raw material demand until 2025, after 2025 we expect other applications, like grid storage and heavy vehicles, to gain momentum.

BATTERY TECHNOLOGY OPTIONS

Electric batteries are at the heart of the EV revolution, and McKinsey assumes they will be central for at least the next five to seven years. But battery chemistries are also at the center of producers' concerns given this linkage to raw material supply.

Cathode composition is the main differentiating factor between Li-ion batteries. Currently, there are five Li-ion battery technologies vying to be the main choice for battery makers, each using a different blend of raw materials. Each type of battery chemistry uses lithium ions as the charge carriers between the anode and the cathode, with the majority having graphite as the anode. These cathode chemistry archetypes are the basis for every producer's cathode "recipe" (see appendix for graphical overview). The five main technologies are:

1. **Lithium cobalt oxide (LCO).** Used extensively in portable electronics, this chemistry has good performance and is relatively safe. However, due to its high cobalt usage, it is relatively expensive and therefore not used in EV applications.

2. **Lithium nickel manganese cobalt (NMC).** This chemistry takes several forms, such as NMC 111 (the simplest, based on an equal amount of the three elements' atoms), NMC 532/622 (with a higher energy density and lower price than NMC 111 due to a lower cobalt content), and the most recent and advanced NMC 811 (with the highest theoretical

performance). NMC chemistries were mainly developed for the EV industry but, with their high performance and relatively low cost, they may well end up being used in other battery applications.

3. **Lithium nickel cobalt aluminium (NCA).** This chemistry was the first commercial attempt to substitute some of the expensive cobalt in the LCO cathode for increased nickel content. It has a good energy density and an affordable price, making it ideal for EVs and portable electronics.

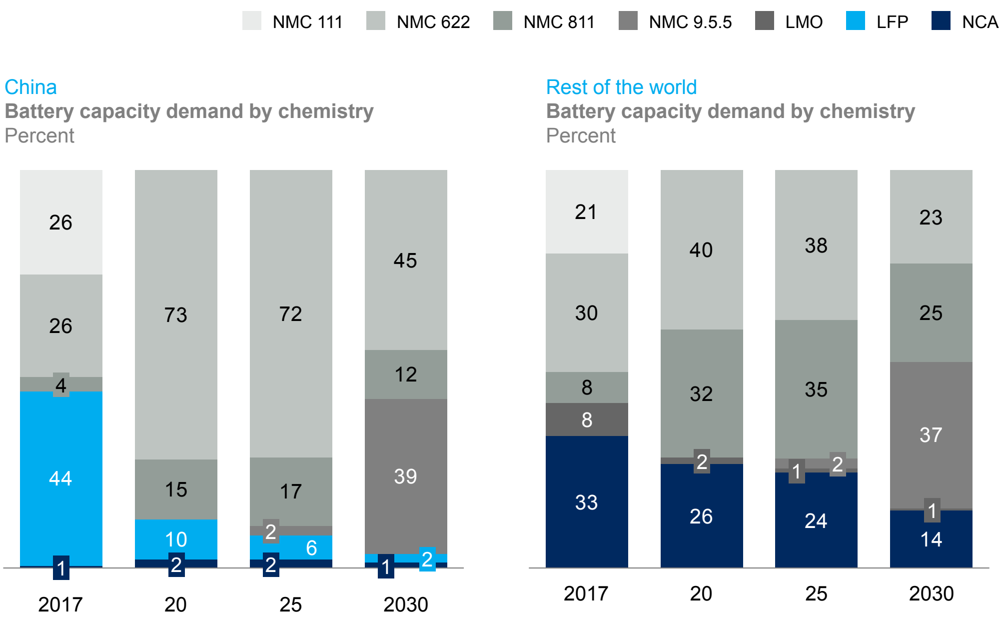
4. **Lithium iron phosphate (LFP).** Intrinsically safer than other cathode chemistries, LFP is not protected by many intellectual property restrictions. Its high-power density makes it an ideal candidate for electric tools and e-buses and a good option for EVs.

5. **Lithium manganese oxide (LMO).** Used in the first EVs, such as the Nissan Leaf, because of its high reliability and relatively low cost. LMO's downside is a low cell durability compared to other competing technologies.

As of 2016, the cathode accounted for approximately 25 percent of a battery pack's costs[4] and hence the choice of raw materials in the cathode is influenced by the impact on the economics of the battery pack. Raw materials used in the cathode, i.e., lithium, manganese, nickel, and cobalt, are becoming increasingly important in the total battery cost. We estimate that raw materials will represent 10 percent of the cost of an EV battery pack in 2018 (around USD 22 of the total 200 USD/kWh) increasing from 3 percent in 2010.

Exhibit 2

Distribution of EV by battery chemistry[1]



1 Other battery demand segments have been excluded

SOURCE: McKinsey Basic Material Institute's battery raw materials demand model

4 This percentage will change based on the chemistry used and the cost of respective materials, as well as battery size (larger batteries may use more metal to hold more charge)

As a result, the recent price spikes for lithium and cobalt have resulted in many battery producers working to reduce the overall material needed per kWh and additionally focus on less cobalt-intensive chemistries. Consequently, NMC chemistries have become automotive OEM's preferred technology in recent years. In the last few months, NCA technologies have pulled ahead; Tesla, which used the NCA technology for its Model S, now deploys a higher performing version for the Model 3 with even less cobalt than an NMC 811 and is working towards reducing the volume of cobalt contained in future batteries.

Exhibit 3 shows the impact of increasing cobalt and lithium prices on the battery pack price, which demonstrates that while lithium prices do influence battery cost, overall battery economics are more sensitive to cobalt prices. It is important to note that while changes in battery raw materials prices will only increase vehicle costs by approximately USD 100 per vehicle, and hence will likely not be a "show stopper," there is increasing concern regarding raw material availability (especially that of cobalt). This concern is increasing the focus on low cobalt batteries and, as a result, the high-performing, low-cobalt, high-nickel NMC 811, and perhaps even the newly proposed NMC 9.5.5 battery (with 9 parts of nickel, and 0.5 of cobalt and manganese).

Exhibit 3

Battery pack costs for NMC 622 and NMC 811 cathodes in different lithium and cobalt price scenarios

Battery pack cost
USD/kWh

Δ, percent to base / Δ, USD to base

Li_2CO_3 price USD/t	2018 NMC 622 cathode Cobalt price USD/lb: 15	25	40	2018 NMC 811 cathode Cobalt price USD/lb: 15	25	40
5,000	-6% 196	-2% 205	+2% 213	-4% 121	-2% 123	0% 126
10,000	-3% 201	~ 208	+5% 218	-2% 124	~ 126	+2% 129
14,600	-1% 206	+2% 213	+7% 223	+1% 127	+2% 129	+5% 132

NMC 622 more sensitive to change in cobalt price vs. NMC 811

SOURCE: McKinsey

Graphene and other battery materials

Significant investments are being made into new battery materials, some to support the current battery chemistries and some to replace them altogether. Graphene is one such new material that scientists are looking to harness for the next phase of the battery revolution. In a recent announcement, Samsung claimed to have developed a graphene-containing Li-ion battery with 45 percent higher capacity and able to charge five times faster than conventional Li-ion batteries. Another technology attracting attention is the solid-state electrolyte. This technology holds several promises, among which is the substitution of the flammable electrolyte liquid found in conventional Li-ion batteries with a solid electrolyte. This will increase the overall safety of the battery and allow the possibility of using a thin film of lithium as the anode instead of the much bulkier graphite powder currently used. A thin film lithium anode will decrease the battery's weight and volume, increasing the energy density.

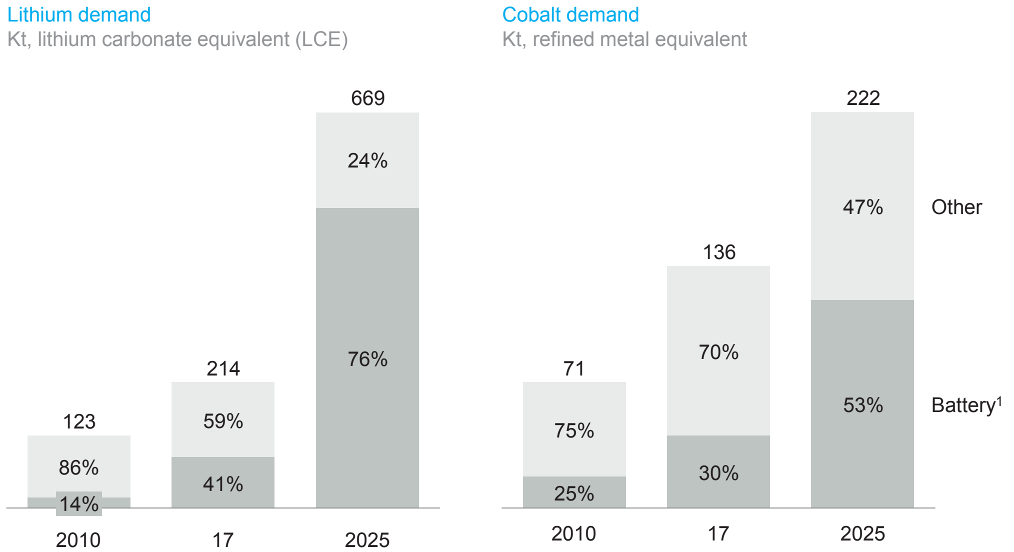
While the introduction of solid-state electrolytes and/or graphene solutions might open new possibilities for new cathode materials, the industry consensus is that, in the foreseeable future, these technologies will not impact cathode chemistry. As a result, these technologies will not influence the demand for cobalt and nickel in the medium term.

New types of batteries are always being put forward – such as zinc air, supercapacitors, and fuel cells – all promising to be the power source of the future. The complication for all these battery types comes down to cost, volume, and weight per kWh, the ability to ramp up to the massive amounts of batteries needed to power millions of vehicles, and the ability to do this all safely and over a long period of time. To date, all these other materials have failed to garner a widespread commercial audience and are expected to remain limited to niche applications.

Based on the above analysis and the impact of the EV revolution, we expect robust demand growth both for lithium and cobalt between 2017 and 2025. Total lithium demand will increase from 214 kt of LCE in 2017 to 669 kt of LCE in 2025 in our base case (with battery and other uses representing 509 kt LCE and 160 kt of LCE respectively) and to 893 kt LCE in the aggressive case. Total cobalt demand will increase from 136 kt refined equivalent in 2017 to 222 kt of refined equivalent in 2025 in our base case (with batteries and other uses representing 117 kt and 105 kt respectively) and to 272 kt refined metal equivalent in the aggressive case.

Exhibit 4

Lithium and cobalt demand evolution split by battery and other applications



1 Battery includes automotive (HEV, PHEV, BEV), trucks and buses (light, medium, heavy), 2- and 3-wheelers, machinery (forklifts and others), grid storage, consumer electronics

SOURCE: McKinsey

Here comes the supply … or does it?

There is an old saying in the industry that "the cure for high prices is … high prices," describing how supply responds to price increases and new capacity is brought to the market, which in turn lowers prices until the market finds a new equilibrium. The recent spike in lithium and cobalt prices and subsequent announcements of supply side additions certainly reflects this dynamic. This response will be welcomed by players in the value chain who fear that raw material supply availability and price spikes may jeopardize the role that lithium and cobalt could play in the future of the EV battery story. However, the supply side dynamics for lithium and cobalt are very different and this will fundamentally impact the mid- and long-term supply, demand, and pricing dynamics.

LITHIUM SUPPLY – THE COMING WAVE

Lithium supply is oligopolistic in structure: there are currently only eight producing countries of which three – Chile, Australia, and China – accounted for 85 percent of global production (equivalent to 216 kt of LCE) in 2017; only four companies – Talison, SQM, Albemarle, and FMC – control most of the mine output. Currently, there is no structural constraint on supply with global production well below industry capacity of approximately 450 kt LCE. For example, the world's largest miner, Talison, is operating at barely 60 percent of its nameplate capacity, which if fully utilised would result in enough production to meet the global lithium demand of the early 2020's. This leads to the question: if there is no supply constraint, why have prices jumped to an average price of USD 19,500/t in 2017 from an average of USD 5,000/t in 2016, and how will this evolve in the future? The answer to this question lies in understanding the development of the global mine supply and processing capacity – the majority of which is in China – as well as future production economics, i.e., the industry cost curve.

Lithium is a very abundant mineral produced from either brines or hard rock sources, with products from clays also in the pipeline. Each producing country currently supplies lithium from just one of these sources, e.g., brines from Argentina, Chile, and Bolivia, and hard rock from Australia. China is an exception as it produces from both brines and hard rock. In 2015, 56 percent of global output was from brines and the remaining 44 percent from hard rock sources. Whilst brines became the dominant source of production in the 1990s due to lower production costs compared with the mining and the processing of hard rock, hard rock lithium has regained its market share and will be a major source of growth moving forward, especially in China. Lithium is sold and used in two main forms, lithium carbonate (19 percent lithium content) largely produced from brines, and lithium hydroxide (29 percent lithium content) largely produced from hard rock sources, which is currently the preferred form for the longest-range EV batteries.

Pricing lithium and cobalt

Unlike many widely used materials in today's conventional vehicles, such as copper, aluminium, and steel, lithium and cobalt come from a far different place in terms of pricing. Both lithium and cobalt have been seen in the past as "minor metals" and do not have high transparency and liquidity around pricing. Lithium contract prices can be as much as 60 percent below the spot price inside of China. The spot price is used predominately in China for speculation rather than large-scale negotiations, and it is rarely used for hedging as with most of the "major" metals. While cobalt trades on the LME, the contract is very illiquid, averaging open interests of just 354 contracts since the beginning of 2016. This pales in comparison to copper, which has an average of 331,000 contracts.

Over time, we believe that the liquidity and transparency for both lithium and cobalt will increase as the markets increase in size. Financial traders are beginning to enter these markets and more liquid contracts could begin to appear. The maturation of these markets will be important to the long-term success of the EV battery material market. Lithium is typically priced via quarterly contracts that are sometimes announced to the market, whereas longer-term deals are based on volume, not a fixed price. Cobalt is less transparent, with deals structured well below the spot price, at various timeframes, and the details of which are not publicly announced. This means buyers must have a full awareness of the market when structuring deals.

Lithium brine production. Lithium brine bodies in salt lakes or salars are formed in basins where water has leached lithium from the surrounding rock. These brines are trapped and concentrated by solar and wind evaporation. Extracting lithium involves pumping the brines into a series of evaporation ponds, crystallizing the other salts out of the brine, and leaving behind a lithium-rich liquor in a process that can take up to two years. This is then further processed to remove impurities, e.g., boron, magnesium, and potassium, before conversion into a lithium carbonate chloride or hydroxide. The economics of different brine processes are dictated almost entirely by the chemical composition of the brine and environmental conditions. The first product made from brines is lithium carbonate (Li_2CO_3), which contains 19 percent lithium. This is roughly twice the concentration of lithium suspended in the original brine. Lithium carbonate can then be processed into a higher-grade lithium hydroxide, but it is an expensive route.

Lithium hard rock production. The most important lithium hard rock minerals are found in granitic pegmatites, of which spodumene (from the Greek for "burnt to ashes") is the most prevalent. To extract the lithium, the rock is first crushed and heated in a rotary kiln. Once roasted, it is crushed into a fine powder, mixed with sulfuric acid, and roasted again. This material then goes through a refining process to increase the lithium concentration and remove unwanted materials, such as magnesium and calcium. Finally, soda ash is added for another round of heating, filtering, and a final round of processing at a conversion plant. The operating costs of these hard rock conversion plants are largely dependent on the prices of key raw materials – spodumene, sulphuric acid, and soda ash – and energy prices. While the cost of producing lithium carbonate from hard rock is far more expensive than from brines, the cost of producing lithium hydroxide from hard rock can be very competitive.

In 2017, the marginal cost of production was estimated to be USD 6,500/t of LCE. Analysis of the cost curve shows that brine operations were much more cost competitive than hard rock operations. SQM and Albemarle were the most competitive major players on the left hand side of the cost curve. Talison was the most cost competitive hard rock producer with the Chinese players positioned in the middle and right hand side of the cost curve (depending on whether they were a brine or hard rock operation). This picture changes slightly when viewed from the perspective of lithium hydroxide, which is likely to take a large share of the overall future demand for lithium, given the preference for its usage in long-range batteries, such as NMC 811 and NMC 9.5.5. Conversion of lithium carbonate produced from brines into lithium hydroxide is more expensive compared to the production from spodumene by ~USD 500/t. This is because spodumene can be directly transformed into hydroxide, while brines first produce a carbonate that then needs to be converted to a hydroxide.

Exhibit 5

2017 lithium cost curve and 2017 average price

2017 global lithium cost curve

USD/t LCE, kt of LCE modelled supply[1]

1 Chinese capacity utilization is modelled at 30% and rest of world at 90%

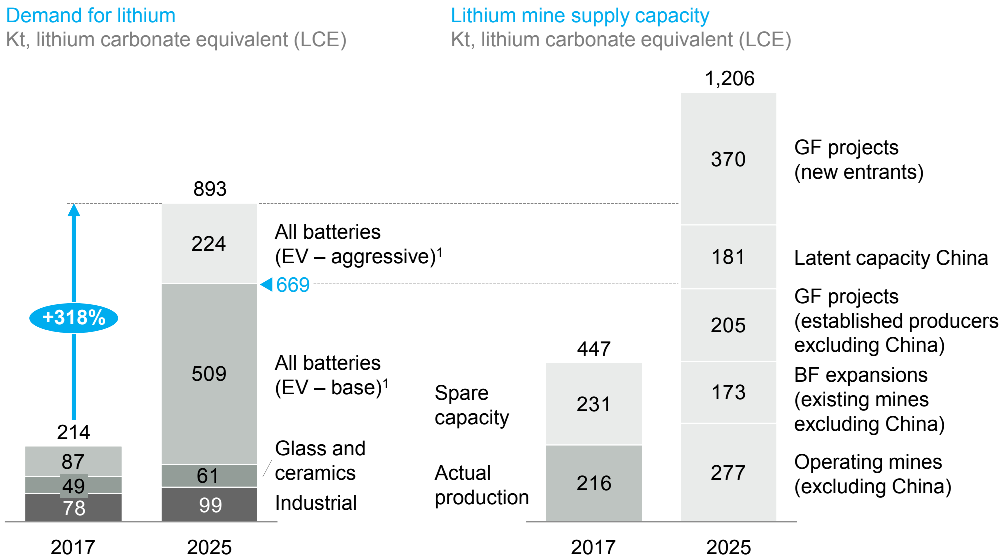
SOURCE: McKinsey Lithium Supply Model; Benchmark Mineral Intelligence; Asian Metal Inc.

Over the long term, the McKinsey MineSpans analysis estimates that the marginal cost of production by 2025 will be in the range of USD 7,000 to 8,000/t of LCE (2017 real terms). Considering the need for some brownfield expansions, this would imply prices of USD 8,500 to 11,500/t of LCE. This is significantly below the average 2017 spot price of USD 19,500/t LCE and the average contract price of approximately USD 12,000/t of LCE, which has been driven both by a lack of rapid production response, strong expectations regarding the EV revolution, and technical difficulties at conversion facilities required to produce battery-grade lithium despite sufficient nameplate capacity. By 2025, our supply pipeline based on current announcements shows a potential addition of 755 kt of LCE capacity above the existing 450 kt of LCE capacity (currently running at only ~50 percent utilization). Of course, not all of this capacity will enter the market as the recent price spikes have started to reverse and many projects no longer look economical. Some highlights from McKinsey's supply model include the following contributions to production growth: Argentina, with ~50 kt of LCE from Rincon's Salar del Rincon project and ~25 kt of LCE from the ramp-up of

Orocobre's Salar de Olaroz expansion project, Chile, with ~15 kt of LCE from the ramp up of Albemarle's La Negra plant and potentially 100 kt of LCE from SQM (the agreement between SQM and the Chilean government could see the company more than doubling the current output in the long term); Australia, with ~85 kt of LCE from the Greenbushes expansion of Talison Lithium (a joint venture of Albemarle and Tianqi). Additionally, projects priced in the USD 8,000/t range are looking increasingly viable, e.g., Pilbara Minerals, Nemaska Lithium, Bacanora, and Altura Mining.

Exhibit 6

Lithium supply and demand 2017 vs. 2025



1 Battery includes automotive (HEV, PHEV, BEV), trucks and buses (light, medium, heavy), 2- and 3-wheelers, machinery (forklifts and others), grid storage, consumer electronics

SOURCE: McKinsey

Finally, based on the announced mine expansions, conversion capacity is not expected to be a structural constraint in the value chain as a similar amount of convertor capacity has been announced. Currently, more than 80 percent of Australian spodumene is exported to Chinese convertors, some of whom, e.g., Tianqi and Ganfeng, are shareholders of producers while others have offtake agreements in place.

COBALT SUPPLY – UNCERTAINTY ABOUNDS

McKinsey MineSpans estimates that in 2017, the total cobalt supply of ~127 to 140 kt was split between mined cobalt of 115 to 125 kt of refined cobalt equivalent and a recycling contribution of 12 to 15 kt. The cobalt mine supply is currently quite fragmented from a producer perspective, with the top three players today accounting for just below 40 percent of global mine supply – Glencore (22 percent), DRC state miner Gecamines (9 percent) and China Molybdenum (7 percent). However, in contrast to lithium, cobalt mine supply is almost monopolistic in structure when looking at regional supply: the DRC alone accounted for almost 70 percent of globally mined cobalt output in 2017, with Russia, Cuba, Australia, and Canada – the next largest supply countries – accounting for just 13 percent of global supply.

Currently, the cobalt industry is responding to the anticipated demand increase, albeit not as aggressively as the lithium industry. McKinsey MineSpans estimates that the industry could add capacity expansions of between 110 and 120 kt by 2025, bringing the total potential mine supply to 225 to 235 kt. Additionally, recycling could provide an additional 20 to 25 kt of supply by 2025, bringing the total refined equivalent cobalt supply to 245 to 255 kt by 2025.

Approximately 40 to 45 kt of the cobalt mine capacity additions by 2025 are expected to come from two projects, both in the DRC. The announced expansion of Glencore's Kamoto Copper Company, operated by the joint venture between Glencore's Katanga Mining (75 percent) and the DRC state miner Gecamines (25 percent), is the largest known expansion project and could add up to 30 kt of cobalt supply annually by the end of 2019. The second largest expansion is the Metalkol Roan Tailings Reclamation (RTR) project from Eurasian Resources Group (ERG), which could add up to 14 kt of cobalt supply annually as early as 2020.

As shown by the two examples, our MineSpans analysis of announced cobalt expansion projects indicates that the DRC will play an even more dominant role in the future cobalt supply. In our base case, DRC will represent ~75 percent of cobalt mine supply globally. Outside of the DRC, the single largest expansion project is the extension of the Mopani Mine in Zambia, contributing an additional volume of 2.5 to 3.0 kt of cobalt annually. No major mine capacity expansion outside Africa is expected in our base case, even though there are several early stage projects in other regions, e.g., Sunrise in Australia.

However, several key issues make an accurate determination of future mine supply uncertain: Firstly, a major and broadly discussed complication of cobalt mine supply is the fact that nearly two-thirds of global mine supply today comes from the DRC and that share is expected to increase even further to ~75 percent. The DRC has historically seen supply disruptions and is currently witnessing changes in its mining law and ownership disputes. Furthermore it is mired in concerns regarding the role of artisanal mining and child labor, which relates to one of the main concerns of cobalt consumers in the automotive and consumer electronics sector: the traceability of the material. Having certainty about the origin of the metal and being sure it is not related to child labor could either lead to a premium for certified material or at least lower the accessible supply for certain end-use sectors. Indeed, this supply risk is one of the main reasons China has increased its focus on this strategic country, e.g., China Molybdenum's acquisition of Freeport-McMoran's stake in the Tenke Fungurume Mine in the DRC. China also has no significant domestic resources of cobalt and 90 percent of China's cobalt units – in the form of ores or as semiprocessed material, such as alliage blanc with ~25 percent cobalt content – are sourced from the DRC.

Secondly – and in contrast to lithium – approximately 90 percent of cobalt mine supply is produced as a by-product, either from copper (55 percent) or nickel (35 percent) mines. That makes several expansion projects not only dependent on the future cobalt demand, supply, and price dynamics, but also on nickel and copper dynamics. In fact, there are only two operating cobalt mines where cobalt is the main product: Mukondo in the DRC (~5 - 9 kt of cobalt production in 2017) and Bou Azzer in Morocco (~2 kt of cobalt production in 2017). By 2025, we expect the supply from copper projects (mines and tailing reprocessing) to increase to ~75 percent, while nickel projects will represent ~20 percent of supply, bringing the share of cobalt supply as a by-product closer to 95 percent. This will result in cobalt being even more dependent on the performance of copper and nickel in the future. Fortunately, in our base case, both metals will see an upside in prices in the coming years. For copper, McKinsey MineSpans estimates prices between USD 6,500/t and 8,100/t by 2022, while for nickel, between ~USD 14,800/t and 17,100/t by 2022.

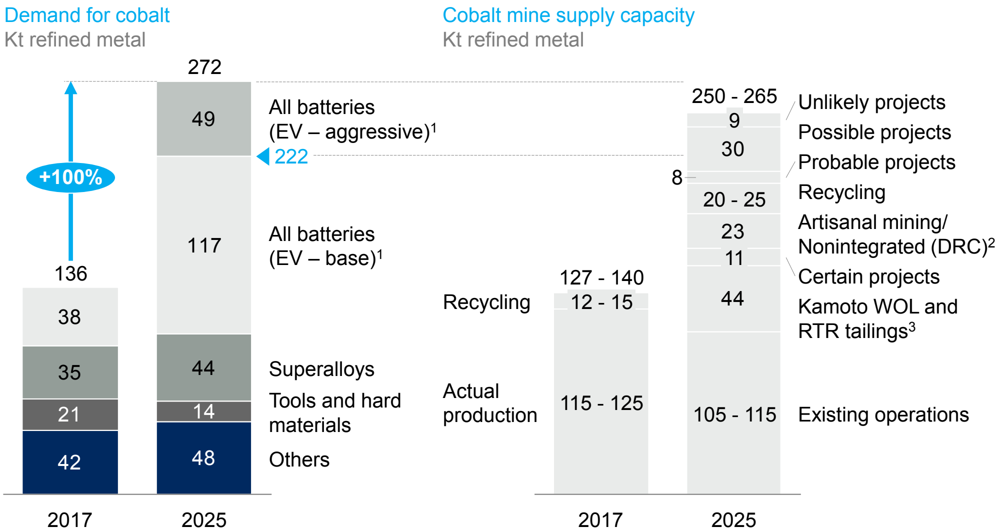
Given the above, McKinsey MineSpans classifies 30 to 35 ktpa of the announced cobalt mine supply additions as certain or probable for 2025. This is in addition to an expected net production capacity increase for existing operations of ~25 to 30 ktpa between 2017 and 2025 (considering the Kamoto ramp-up). On the other hand, ~40 to 50 ktpa of announced expansion projects have been classified as unlikely or not possible and are not considered in our base case.

Besides the availability of mining capacity, the processing and refining of cobalt-rich raw materials into battery-grade products may present a further challenge in terms of transparency and capacity. Over the last few years, McKinsey MineSpans estimates that global cobalt mine supply has been consistently above 100 kt of refined supply per year and, at the same time, reported refined production has been consistently below that, in the range of 80 to 95 kt per year. This gap could be explained by a combination of several factors, including the buildup of significant inventories of intermediate product (on top of existing final product inventories) and the possible direct sales of unrefined material to some of the end applications.

Similar to the regional concentration of cobalt mine supply, cobalt refining capacity is regionally concentrated with ~50 to 60 percent of the global refining capacity located in China. The largest refineries outside China are Freeport Cobalt's Kokkola refinery in Finland with an annual production of ~11 kt, Glencore's Nikkelverk refinery in Norway with an annual production of ~5 kt, and Sumitomo's Niihama refinery in Japan with an annual production of ~4 kt. If midstream producers and OEMs in other regions are to use the increased cobalt mined supply, additional investments in refining capacity outside of China will be needed (e.g., for increased recovery of cobalt in existing nickel and copper operations). OEMs, smelting, and refining companies will need to assess the technical and economic viability of such investments. Due to the lack of transparency and capacity outside of China, additional obstacles may still emerge along the value chain, even if there is enough cobalt mine supply to meet demand.

Exhibit 7

Cobalt supply and demand 2017 vs. 2025



1 Battery includes automotive (HEV, PHEV, BEV), trucks and buses (light, medium, heavy), 2- and 3-wheelers, machinery (forklifts and others), grid storage, consumer electronics

2 Includes nonintegrated capacity which is reliant on purchased ore and/or preconcentrate from smaller and/or artisanal operations. This capacity is not tracked on a mine-by-mine basis, but tracked on a processing plant level, assumed to be fed by mines not tracked individually in the other buckets

3 Large increase explained largely by ramp-up of whole ore leach operations by Glencore, already commissioned, and tailings recovery (RTR project) by ERG, expected to be commissioned by the end of 2018. Together accounting for ~41 kt

SOURCE: McKinsey

WHAT ABOUT RECYCLING?

Although cobalt has been historically recycled given its high value and application in alloys, Li-ion battery recycling is currently in its infancy. The industry is currently mainly concerned with the disposal of potentially hazardous used consumer electronic products rather than extracting the materials for reuse. We estimate that in 2017, 12 to 15 kt of cobalt was recovered from recycling, while virtually no lithium was recovered.

Currently, there are no well-defined routes available for the recycling of Li-ion batteries; however, there are numerous prototypes combining pyrometallurgical and hydrometallurgical routes attempting to extract the valuable metals. We expect that the industry once invests and finds an optimal recycling route when the first wave of "exhausted" EV batteries becomes available, the industry will have higher volume with a more homogeneous feed compared to what is currently available. Before recycling accelerates, we expect reuse to dominate the used EV battery market. After primary usage in EVs, used batteries are expected to retain 60 to 80 percent of initial capacity, encouraging their reuse in other applications such as grid storage. As a result, in our base case, we estimate that by 2025, 20 to 25 kt of cobalt will be recovered through recycling with only ~4 kt of LCE generated via recycling.

SUPPLY AND DEMAND SUMMARY

Given the increase in lithium supply over the next several years, we see a balanced market for lithium by 2025 in our base and aggressive EV scenarios. However, certain qualities, e.g., lithium hydroxide, might see price increases in the short term due to refining obstacles. We expect a brownfield pricing regime where current producers see healthy profits and larger investments in new high-cost projects experience more pressure. This pricing regime will be sustained by a strong growth in demand and – with a market centered on a few large producers – it is unlikely that prices would drop below the marginal cost of production on a sustained basis. Similarly, prices are unlikely to see spikes on a sustained basis as new capacity is readily available and will be brought online to ease any tightening of the supply demand balance.

For cobalt, the determining factor will be whether our base or aggressive EV case materializes. In our base case analysis, it is likely that there will be enough material available for the market until 2025. However, if the aggressive case were to occur, we could see a shortage of cobalt occurring after 2022. For both scenarios, the pace at which additional cobalt mine capacity reaches the market will be key. Under the aggressive case, a move to a higher-nickel, lower-cobalt battery chemistry would be more likely as the market explores different strategies to balance the EV revolution with the available cobalt supply.

It is extremely challenging to accurately determine future cobalt price dynamics given that, by 2025, ~95 percent of cobalt production will be a by-product of either a copper or nickel mine. Similar to other commodities where supply is heavily dependent on by-product, price setting mechanisms are typically driven by the willingness of customers to pay for an equally feasible, cost competitive substitute rather than pure economics and the marginal cost of production.

In this respect, two commodity analogies can be drawn with cobalt: in the case of palladium – produced as a by-product from nickel, copper, and platinum mines – prices increased fourfold from early 1998 to early 2001 from ~USD 250/oz to close to USD 1,000/oz and then fell back to their previous levels of USD 300 to 400/oz in the subsequent years. This price volatility was primarily linked to the perceived availability of material influenced by inventory building and not linked to the economics of new or existing supply. Similar to cobalt, a suitable substitute existed for the usage of palladium in autocatalysts and, consequently, there was an increase in substitution by platinum as palladium prices spiked.

In the case of ferroniobium – a market with historically highly concentrated raw material supply and technically in oversupply – prices were significantly higher than the marginal cost of production, with an upper price limit defined by substitution economics. However, price volatility was not at all comparable to the volatility seen in cobalt or palladium as niobium supply was relatively stable and certain, and a fundamental demand disruption, such as the EV growth being witnessed currently, was lacking.

Given its increasing supply exposure in DRC and the speed and trajectory of EV adoption and battery chemistries, we believe cobalt prices will continue to see high volatility due to supply uncertainties and lack of transparency rather than a fundamental resource scarcity.

Implications for industry players

Both lithium's and cobalt's future will depend on several determinant variables: the extent and speed of EV adoption, the battery technology that becomes the industry preference, and the supply-side response to the changing demand picture. Uncertainty abounds regardless of where a company sits along the EV battery raw material chain today and thoughtful consideration of the industry's future dynamics is required to make the right strategic moves.

Mining companies need to show that they will be able to provide the raw materials required by the end users while balancing the pursuit of attractive profit pools generated by recent price increases and the potential demand destruction caused by end users' concerns on continued price escalation. To accomplish this, miners need to become what analysts call "long-term greedy." Instead of looking for short-term profits, miners need to partner with battery suppliers, automakers, and financial players to create a larger market for their materials. This may include: partnering with battery manufacturers to shape existing technologies to ensure a stable and cost competitive supply of necessary materials to customers; working with financial players to access cost competitive, long-term funding to ensure the timely development of new capacity; and facilitating the development of a liquid contract market to help users and producers hedge out price risk.

Battery producers and automotive OEMs will need to develop sourcing strategies to ensure a stable supply of lithium and cobalt to insulate them from the risk of shortages and potential price spikes. Clearly, cobalt represents the most pressing challenge and users will need to look at their battery R&D to find diversifying technologies that will avoid the potentially supply-constrained raw material. This is already taking place, with the development of the NMC 811 battery and initiatives to use even less cobalt in future batteries. This uncertainty may require automakers to keep several "irons in the fire," as new technology trends could rapidly change the leading technologies for batteries. The prospect of such changes may require automakers to have a medium-term strategy and a separate longer-term strategy to account for developments in new technologies, such as solid-state batteries, graphene-based batteries, and even zinc-air batteries. Like mining companies, battery producers and automotive OEMs need to think beyond substitution, e.g., partnering with mining and smelting and refining companies, to provide security of supply as well as transparency and traceability of the material along the value chain from the mine to the battery installed in the car.

Financial players will also have a role to play in the evolution of the industry in two important respects: 1) in the financing of EV materials, from direct equity investments to streaming agreements and helping companies in the EV battery value chain hedge their financial risks and 2) in working with global exchanges and intermediaries to help increase market liquidity via new spot market mechanisms as well as futures and derivative products. We are already seeing the financial backing of new supply via streaming deals which provide the up-front capital required in exchange for a long-term fixed-price material. It is also possible we could see an asset-backed ETF which purchases metal to be held as a more liquid option than the illiquid exchange trades. Private equity players may also be new investors in mines as the returns could entice cash-rich funds to make investments.

In conclusion, to realize the strong growth prospects of the lithium and cobalt industries, all participants – from mining companies to battery and automotive OEMs to financial players –

will need to understand the battery value chain as an "ecosystem" and work with each other to provide transparency and agreement on key areas, such as battery technology, supply side growth, and pricing mechanisms to ensure the new era for battery raw materials is truly golden and not just gilded.

The authors wish to acknowledge the contributions of Sigurd Mareels and Jukka Maksimainen in the development of this article.

Appendix

Exhibit 8

Battery technologies by chemistry with pros and cons

Key performance metrics of cathode chemistries

Cathode level metrics

Strong | Moderate | Weak

Material	Description	Safety	Cost USD/kWh	Energy density kWh/kg	Cycle life Times	Ni content Kg/kWh
LCO ($LiCoO_2$)	Mostly applied to consumer electronics. Limited application for xEVs (e.g., Tesla)	Low	Low	0.58	1,500 - 2,000	0
NMC1 ($LiNi_xCo_xMn_xO_2$)	Applied mainly in consumer electronics but increasing application for xEVs	Mid	Mid	0.60	2,000 - 3,000	0.69 (51 wt[2]%)
LMO ($LiMn_2O_4$)	Relatively mature technology. Applied in xEVs by Japanese OEMs (e.g., LEAF, iMiEV, Volt)	High	High	0.41	1,500 - 3,000	0
LFP ($LiFePO_4$)	Relatively new technology applied in xEVs and ESS. Driven by A123 and Chinese manufacturers (e.g., BYD, STL)	Very high	High	0.53	5,000-10,000	0
NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$)	Applied mostly in consumer electronics (often blended with other chemistries) and e-vehicles (e.g., Tesla)	Mid	Mid	0.72	NA	0.68 (49 wt[2]%)

1 For 811 configuration   2 By weight

SOURCE: Yoshio, M. et.al. 2009, Lithium-Ion Batteries: Science and Technologies, New York: Springer; McKinsey BMI battery materials demand model

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