Disruptive Effect of Battery Recycling on the Near Future Cobalt Market

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Cobalt, along with lithium, nickel, manganese and graphite are considered the drivers of the Fourth Industrial Revolution, due the high demand for Li-ion batteries. Cobalt accounts for 26% of the battery's cost and is important for improving energy density and performance. Cobalt has seen a 150% price hike from January to December 2017, with the same predicted trend for 2018. The Democratic Republic of Congo will continue to dominate the African share of supply, but continue to struggle with political instability. An alternative supply of cobalt in the near future is recycled batteries. Once a critical mass of defective or old batteries is available for extracting materials, it will have a disruptive impact on the cobalt market and price. It is projected that by 2025 the batteries being produced now will reach the end of their productive life. These recycled batteries will then be able to supply up to 10% of the market demand.

INTRODUCTION

Rising demand amid the electric vehicle boom and a lack of major alternative sources has seen cobalt prices more than triple since the start of 2016 (Bloomberg, 2018a). The predicted rise in electric vehicle production to 118 million units will require annual cobalt production of 314 000 tons by 2030. Most electric cars are powered by lithium–nickel–manganese–cobalt (NMC) batteries, which use a cathode composed of nickel, manganese and cobalt and a graphite anode (Reuters, 2017). Cobalt's price surged from USD 10 to USD 30 per pound in less than two years, but gains are poised to slow to USD 32 by 2021 and USD 41 by 2022, according to forecasts of Macquarie Group Ltd (Hirtenstein, 2017).

It is anticipated that by 2025 there will be sufficient volumes of cell phone and electric vehicle batteries that reach the end of their productive life to justify large-scale recycling operations. Electric vehicle batteries have an effective life of between eight and ten years (Reuters, 2017). These operations will focus on reclaiming as much as possible of the battery metals, at a fraction of the cost of mining and processing of the ore. It is estimated that the recycled batteries will be able to supply up to 10% of the market demand for cobalt. In parallel, development of batteries that require less cobalt is also underway and will favour cobaltite sourced from recycling.

PRIMARY COBALT SUPPLY 2018/19

The Democratic Republic of Congo (DRC) produces more than half of the world's cobalt. In 2017, the country produced 81 000 tons of cobalt (Bloomberg, 2018b). Cobalt is produced as a by-product of copper and nickel mining. Half of the production comes from the country's two largest copper mines: China Molybdenum-controlled Tenke Fungurume Mining and Glencore-owned Mutanda Mining (Bloomberg, 2018b). A new mining law signed by Congolese President Joseph Kabila on 9 March 2018 will result in royalty rates on cobalt export revenue rising fivefold to 10% (CNBC, 2018). Additionally, a new 50% tax on so-called super profits, defined as income realised when commodity prices rise 25% above levels in the project's bankable feasibility study, would be introduced (CNBC, 2018).

By 2019 the production of cobalt in the DRC is set to increase due to several mines coming into production. Chemaf is building a processing plant at its Mutoshi mine in Lualaba province, capable of producing 20 000 tons of cobalt a year, adding to Etoile mine's 5000 tons per year (Bloomberg 2018b). Glencore's Katanga Mining is set to re-start production after being under care-and-maintenance for two years and could produce up to 34 000 tons of cobalt a year (Bloomberg, 2018b). Eurasian Resources Group Sarl's Metalkol Roan Tailings Reclamation project is set to reach a capacity of 21 000 tons a year (Bloomberg, 2018b). Shanghai-based Pengxin International Mining's Shituru Mining will also open a plant with a capacity of 7000 tons annually (Bloomberg, 2018b).

The world will remain dependent on the DRC as the primary supplier of cobalt as major deposits in Australia or Canada are yet to be developed and could take several years to reach commercial production. China has tight control over refined output, currently producing more than half of the world's refined cobalt and 85% of cobalt oxides, salts and other chemicals (Lazenby, 2017). It is also expected that miners will start opting for a new sales model, where highly volatile metals, such as cobalt and nickel, will no longer be sold at a fixed price.

COBALT IN RECHARGEABLE BATTERIES

Cobalt is critical to battery chemistries; the cathode represents about 26% of the battery's cost and is important for improving energy density and performance (Lazenby, 2017). On the back of rising cobalt prices, the electric vehicle industry is actively looking to replace cobalt in battery chemistries. More research is being done on the development of batteries using more nickel, including nickel–cobalt–manganese batteries in which the ratio of nickel is as much as 88% (Bloomberg, 2018a). Increase in the nickel proportion, however, reduces the stability of the battery and so it has an impact on cycle life and the ability to charge it fast (Reuters, 2018).

MARKET DRIVERS

Battery Demand

Campaigns like EV30@30 (IEA, 2017) aims to achieve the goal of 30% market share for electric vehicles, significantly boosting demand for energy capture, storage and delivery infrastructure and associated raw materials. Technologies are creating rapid demand for battery chemistries to generate maximum energy density. The demand for cobalt will rise from 8% in 2016 to 23% in 2021, just to meet the projected electric vehicle demand. Cobalt metal is expected to remain in strong deficit this year (2018), with the projected price expected to rise to USD 92 000 per ton as demand rises 10% and in spite of a 14% higher supply response. Forecasts point toward electric vehicles reaching cost parity with internal combustion engines by 2025, and roughly 140 new Tesla-sized giga-factories will be required by 2035 to satisfy new and replacement battery demand (Bloomberg, 2017a).

Ethically Sourced Ore and Environmental Policies

The London Metals Exchange's probe into ethical, inelastic supply of cobalt from the DRC is expected to increase the strain on transparent, responsible mining operations (Creamer Media Reporter, 2017). Ethically sourced products have also gained traction amongst socially aware consumers, placing pressure on producers to be able to prove their metal was ethically sourced. The DRC has an unfortunate history of conflict mineral sales and the use of child labour. Chinese actions in recent years to embrace temporary production cuts and enforce stricter environmental regulations have already disrupted a range of commodities, including cobalt. In a bid to curb air pollution, China aims for electric cars to make up 10% of new sales in two years (Lazenby, 2018). Electric vehicle batteries can weigh up to 500 kg each and can have a significant environmental impact if they are discarded in increasingly larger hazardous-waste sites. It is also possible to use old batteries with decreased capacity or refurbished batteries in solar power grid storage systems. Owing to the size of these batteries, it is envisaged that the application or re-use of batteries in this way will be limited to warehouse or remote sites rather than domestic use. Practical consideration would also have to be given to the number of recharge cycles these batteries would be able to sustain before becoming uneconomical, even in this application.

COBALT RECYCLING

Demand

The commercialisation of closed-loop multi-metal recycling of batteries represents a fundamental new industry with significant revenue potential. A trend has developed among battery makers to reduce dependence on the DRC as a source of cobalt. Samsung SDI, Volkswagen, BMW and Panasonic are developing processes to secure future supply of cobalt through cell phone and electric vehicle battery recycling (Kim, 2018). Recycling will be essential because mining of raw materials will not be enough to meet the world's needs if electric vehicle demand continues to rise at the current pace beyond 2025.

Sources

Smartphone batteries contain 5 to 20 g of cobalt. The technologies to extract minerals from cell phone batteries that reach the end of their useable life, could add 25 000 metric tons of supply by 2025. In 2018 Samsung Electronics was able to source 157 t of cobalt, copper and other minerals from recalled Note 7 smartphone batteries (Dunne, 2017). Up to one in every ten cell phone batteries does not pass quality control and, if not recycled, would end up on a hazardous-waste site. At present production rates, that equals 4000 tons of cobalt that can be recovered. Cobalt from lithium-ion batteries could reach 22 500 tons in 2025, up from 8700 tons in 2017, according to Creation Inn (Burton, 2017).

Once cobalt supplies sourced from cell phones batteries stabilise, companies like Toyota Motor Corp and Panasonic plan to start extracting materials from used hybrid electric vehicles, which contain about 4 to 14 kg per vehicle battery (Hirstenstein, 2017). According to Bloomberg New Energy Finance (2017), it is anticipated that 311 000 tons of electric car batteries would have reached the end of their productive life by 2025.

Profitability

Umicore, recycling batteries for Tesla and Toyota, uses smelting and leaching to recover metal from cathode materials (Sanderson, 2017). One problem is that lithium-ion batteries in electric cars use a variety of chemical processes, making it difficult to develop a standardised recycling process. The main obstacle battery recyclers face now is a shortage of spent batteries to recycle to make their technology cost-effective. At current commodity prices, approximately 4000 tons per year of batteries are needed to justify the estimated capital costs (Harvey, 2017). American Manganese has indicated that it can extract metals at a cost of about 30 cents per pound and resell them to battery manufacturers for up to USD 20 per pound (Bloomberg, 2017b). For recycling to profitable, 90% of the cathode metals must be recovered during recycling. A 1000-pound lithium cobalt battery contains about USD 6000 worth of cathode material at the top end of the value chain and about USD 1700 for a nickel–cobalt–aluminium battery at the low end, at the time of writing this article. Cobalt is the metal component that makes recycling of small volumes of batteries profitable; excluding it would make the process uneconomical.

RECYCLING METHODS

Recycling lithium-ion batteries (LIB) is an incredibly complex and expensive undertaking that includes: collection and reception of batteries; burning of flammable electrolytes; neutralization of hazardous internal chemistry; smelting of metallic components; refining and purification of recovered high value metals; and disposal of non-recoverable waste metals or materials.

The five components that make up lithium-based batteries, both primary and LIBs, are: the anode, cathode, electrolyte, separator and casing. In both primary lithium batteries and LIBs, the electrolyte is made up of a lithium salt dissolved in an organic solvent. In primary lithium batteries, the anode is lithium metal. Lithium manganese battery accounts for 80% of the primary lithium battery market (Saloojee and Lloyd, 2015). In LIBs, the cathode is an aluminium plate coated with the cathode material, which is a lithium metal oxide. The anode is a copper plate coated with graphite. Polyvinylidene fluoride (PVDF) is used to bind the electrode coating to the plate. The most current Li-ion battery recycling process, after Saloojee and Lloyd (2015), is summarised here.

Recupyl Process

The process uses a combination of physical and chemical treatment steps. The battery scrap is first crushed and put through magnetic and density separation to produce a fine powder. The powder is fed to a hydrometallurgical process, consisting of hydrolysis, leaching and precipitation steps. Lithium is recovered as Li_2CO_3 and cobalt is recovered as cobalt hydroxide.

Crushing of the batteries is a two-step process, taking place in a rotary shredder. The crusher operates in an atmosphere of CO_2 and 10–35% argon (Tedjar and Foudraz, 2010). The CO_2 reacts with any elemental lithium to form Li_2CO_3, which is less reactive than elemental lithium. The crushed batteries are fed to a physical separation process. Some of the off-gas from the crushing step is used to create an inert atmosphere above the hydrolysis reaction. The remaining off-gas is fed to the lithium precipitation step.

The components of the crushed battery scrap are separated by screening, magnetic- and densimetric separation. For the screening step, vibrating screens of 3 mm and 500 μm are used (Tedjar and Foudraz, 2010). The −3 mm fraction contains metal oxides and carbons. The powder is further screened on the −500 μm screen; this fraction is rich in cobalt and lithium. The +500 μm fraction is rich in copper. The cobalt-rich fraction is sent to the hydrometallurgical treatment process and the copper-rich fraction is combined with the steel and sold. The +3 mm fraction is treated by magnetic separation.

The magnetic fraction contains the steel from the battery casings. The non-magnetic fraction is further separated on a densimetric table. The low-density, non-magnetic fraction contains paper and plastics. Non-ferrous metals report to the high-density, non-magnetic fraction. Each of these fractions is sold.
The fine material from the physical separation process is treated by hydrolysis. The material is suspended in stirred water. A solution of lithium hydroxide is added to achieve a pH of 12–13 (Tedjar and Foudraz, 2010). Lithium from the electrodes dissolves to produce lithium salts in solution. The hydrolysis reaction generates hydrogen. Inert gas from the crushing step is used to vent off the hydrogen. The metal oxides and carbon are suspended in solution and are separated out by filtration. The lithium-containing solution is sent to a lithium precipitation step.

Lithium is precipitated from the alkaline leach solution as Li_2CO_3, using CO_2 gas. The source of CO_2 is the off-gas from the crushing stage. Precipitation occurs at pH 9, achieved by the addition of acid. The precipitate is washed with a CO_2-saturated solution and dried at 105°C (Tedjar and Foudraz, 2010).

The stream containing suspended solids from the hydrolysis step is leached in sulfuric acid at pH 3 and a temperature of 80°C (Tedjar and Foudraz, 2010). The metal oxides dissolve, leaving carbon in the residue. The leach product is filtered and the solution is purified prior to cobalt precipitation. In the purification process, copper and iron are removed from solution. Copper is cemented out by the addition of steel shots. Soda is added to increase the pH to 3.85 to precipitate iron. The copper- and iron-free solution is fed to cobalt precipitation. Cobalt is recovered from solution either by electrolysis, or by precipitation as $Co(OH)_3$ through the addition of sodium hypochlorite. The remaining solution contains some lithium and is sent to the lithium precipitation step.

Umicore Process

This is a pyrometallurgical process that uses the patented IsaSmelt furnace technology. The process treats LIBs and nickel metal hydride (NiMH) batteries. There is no pre-treatment of batteries prior to smelting. Cobalt and nickel are recovered from the alloy phase and lithium is lost to the slag. The IsaSmelt furnace is a furnace with a top-submerged lance. Batteries are combined with limestone, sand, coke and slag formers and fed to the furnace through the lance. The feed contains 30–50% battery scrap to produce a product with an economically viable content of cobalt and nickel (Cheret and Santen, 2007). Air is fed from the bottom of the furnace. The air is pre-heated to 500°C. The furnace is divided into three temperature zones: the pre-heating zone, the plastic pyrolysing zinc and the smelting zone. In the pre-heating zone, at the top of the furnace, temperatures are maintained below 300°C. The furnace feed is heated in this zone by gas flowing counter-currently from the hotter zones below. The electrolyte evaporates in this zone. Slow heating of the feed reduces the risk of explosions in the furnace. The middle zone of the furnace is the plastic pyrolysing zone. The temperature is this zone is around 700˚C. The plastic is removed from the batteries by pyrolysis. This is an exothermic process, and the energy released is used to heat the gases which move upward to the pre-heating zone.

The remaining material is reductively smelted in the smelting zone, at the bottom of the furnace. Smelting takes place at temperatures of 1200–1450°C. In the smelting zone, a flow of pre-heated, oxygen-enriched air is injected via tuyeres into the bottom of the furnace. Copper, cobalt, nickel and some iron report to the alloy phase. The slag phase contains lithium oxide, as well as oxides of other metals, including aluminium, silicon, calcium and the remaining iron. The slag is formed into concrete blocks and sold to the construction industry. The alloy phase is treated in a hydrometallurgical process.

The off-gas from the furnace is heated in a post combustion chamber to above 1150˚C using a plasma torch. Calcium, zinc oxide or sodium products are then injected into the combustion chamber to capture halogens evolved from electrolyte and binder evaporation. Water vapour is then injected into the gases to cool it down to 300˚C. This is also to avoid recombination of organic compounds with toxic, flammable compounds such as halogens, dioxins and furans. Copper, cobalt, nickel, zinc and iron are recovered from the alloy phase by dissolution and precipitation. The cobalt and nickel products are $CoCl_2$ and $Ni(OH)_2$, respectively. The $CoCl_2$ is used to produce $LiCoO_2$.

Toxco Process

This is a hydrometallurgical process for the recycling of spent LIBs. The process entails pre-treatment of the batteries, separation of battery components, leaching, solution purification and lithium precipitation.

A pre-treatment step is necessary to render the lithium and by-products inert. In the Toxco process, this is done by cryogenic cooling (McLaughlin and Adams, 1999). The batteries are cooled to between −175°C and −195°C with liquid nitrogen. At these temperatures, the reactivity of the battery material is sufficiently low that there is no risk of explosion. The low temperatures also make the plastic casing of the batteries brittle, so that they can easily be broken. Batteries that have been completely discharged may bypass this step.

The cooled batteries are shredded and sent to a hammer mill, where the batteries are milled in a lithium brine. Lithium dissolves in the hammer mill. The salts formed in solution include LiCl, $LiCO_3$ and $LiSO_3$. The mill is fitted with a screw press, to separate the lithium-containing solution from the undissolved product, referred to as "fluff". The solution will contain some undissolved fine material, consisting of metal oxides and carbon. The fluff component is separated on a shaking table. This produces a low density stream consisting of plastics and stainless steel, and a high density, copper-cobalt product. Both these products are packaged and sold.

The lithium-containing solution is fed to a holding tank prior to filtration. The pH of the solution is maintained at 10 by the addition of LiOH. This is used instead of NaOH to prevent contamination of the lithium product with Na. The material from the holding tank is filtered on a filter press. The cake contains metal oxides. The remaining solution is fed to dewatering tanks. Water is evaporated from the lithium-containing solution. The concentration of the lithium salts increases until the salts precipitate out.

The product from the dewatering tanks is filtered in a filter press and purified with an electrolytic membrane. The filter cake contains 28% moisture. This is then fed to a purification step. A solution of mild sulfuric acid is added to the filter cake, resulting in the dissolution of the metal salts. Li^+ ions pass through the membrane and precipitate as LiOH. The LiOH is converted to Li_2CO_3 by the addition of CO_2. The Li_2CO_3 is filtered, washed, dried and packaged. The remaining solution is disposed.

Inmetco Process

With this method spent batteries form a secondary feed to the furnace, in addition to waste containing nickel, cadmium and dolomitic, carbon and chromium refractories. Process steps include feed preparation, reduction, melting and casting. Iron, nickel, copper and cobalt are recovered in an alloy. Lithium is lost to the slag phase, while the organic electrolyte and the plastic casing are volatilised (Liotta *et al.*, 1995).

The battery feed to the process is prepared by opening up the batteries, removing the plastic and draining the electrolyte and the batteries are then shredded. The other solid feeds to the process are blended and a carbon-based reductant is added and the mixture is pelletised. Liquid waste that contains nickel and cadmium is added at the pelletising stage. The pellets are combined with the shredded batteries and fed to the reduction step.

Reduction takes place in a rotary hearth furnace operating at 1260°C. The residence time is 20 minutes, during which the metal oxides are reduced to metals. Off-gas from the rotary hearth furnace is scrubbed and the scrub solution is sent to a wastewater treatment facility, from which treated water is recycled to the process. Cadmium, zinc and lead are recovered in the wastewater treatment process and sent to another facility for metal recovery.

The reduced product from the rotary hearth furnace is fed to a submerged electric arc furnace (SEAF) for smelting. The SEAF produces an alloy containing iron, nickel, chromium and manganese. The alloy is tapped from the furnace and fed to a casting step. The slag is sold as an aggregate for building. Off-gas from the SAEF is passed through a baghouse before it is discharged to the atmosphere. In the casting step, the alloy is cast into stainless steel "pigs". The molten metal is poured into moulds, which are cooled with water. The pigs are sold to the stainless steel industry. The typical composition of pig alloy is 10% nickel, 14% chromium and 68% iron.

CONCLUSION

It is anticipated that primary cobalt ore, mainly from the DRC, will continue to dominate the market in the short term. Projections suggest that within 10 years the currently produced cell phone and electric vehicle batteries will reach the end of their productive life. This will create a critical mass around the year 2025 in terms of material available for recycling that will make it profitable to operate large facilities. The recycled material will be able to provide up to 10% of the cobalt market demand at that time. Other factors, such as ethical sourcing of raw product materials and environmental policies, will benefit recycled cobaltite as the preferred source of material for new batteries. Even if there is a decrease in the volume of cobalt required for batteries, cobalt will still remain a critical element for effectiveness. Recycling methods are also anticipated to become cheaper and more effective in recovering metals from cathode material. It is therefore suggested that recycling of cobalt will be one of the main disruptors of the cobalt market in the near future.

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