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How will Increased Demand for Electric Vehicles Influence the Price and Production of Cobalt and Lithium?

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Acknowledgement

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All the errors in this thesis are our own. We are neither geologists nor chemists but have done our best to acquire the knowledge that has been relevant for our research question.

Ingrid Kvassheim & Maria Elise Rød Ås, 11.05.2018

Abstract

The demand for electric vehicles is predicted to increase drastically mainly due to climate concerns. Lithium and cobalt, two metals used in the battery for electric vehicles have therefore gained more attention as there is uncertainty regarding future availability. The prices of cobalt and lithium have risen considerably in the last two years due to increased demand for electric vehicles, hence increased demand for the metals. Thus, in this thesis we investigated how increased demand for electric vehicles will influence the price and production of cobalt and lithium. By simplifying the demand and supply functions and modelling them on reduced form, we obtain the covariation between electric vehicle sales and the metal prices. Thereafter, we discuss whether these relationships remain stable.

The results of the estimations indicate that the price of cobalt and lithium will rise by 5.5 and 6.3 percent per annum, respectively, if the demand for electric vehicles rise sharply. In order to reduce the risk of running out of input factors for the electric vehicle production, it is reasonable to believe that battery and electric vehicle manufacturers will store cobalt and lithium. Thus, the demand for the metals will be higher than what the assumed growth in electric vehicle sales suggests. An inelastic supply curve, in combination with a greater shift in demand, will lead to a higher short-term price growth of both cobalt and lithium than the model predicts.

Technological development in extraction, increased secondary supply from batteries, and the completion of new mines following 2022, lead to a positive shift in the supply curve and make it more elastic. Advancements in battery technology will reduce the amount of cobalt and lithium in the battery. Consequently, the impact of increased demand for electric vehicles will have less effect on the demand for the metals in the long run. Due to these dynamics in interaction, the price of cobalt and lithium will in the long term stabilize at a lower level than the observed prices in December 2017.

Sammendrag

Det er spådd en meget sterk global økning i etterspørselen etter elbiler hovedsakelig på grunn av et mål om å redusere CO_2 utslipp. Litium og kobolt, to metaller som anvendes i elbilbatteriet har dermed fått økt oppmerksomhet da det er usikkerhet vedrørende fremtidig tilgjengelighet. Som følge av økt etterspørsel etter elbiler og dermed økt etterspørsel etter metallene, har prisen på kobolt og litium steget betraktelig de to siste årene. I denne masteroppgaven undersøkte vi dermed hvordan økt etterspørsel etter elbiler vil påvirke pris og produksjon av kobolt og litium. Ved å modellere forenklede etterspørsels- og tilbudsfunksjoner på redusert form, finner vi sammenhenger mellom metallprisene og elbilsalg. Deretter diskuteres det om disse relasjonene forblir stabile.

Resultatene fra estimeringen viser at prisen på kobolt og litium vil stige årlig med henholdsvis 5,5 og 6,3 prosent dersom etterspørsel etter elbiler stiger kraftig. For å redusere risikoen for å gå tom for innsatsfaktorer til elbilproduksjonen, er det rimelig å anta at batteri- og elbilprodusenter vil lagre kobolt og litium. Dermed blir etterspørselen etter metallene høyere enn den antatte veksten i elbilsalg tilsier. En uelastisk tilbudskurve kombinert med større skift i etterspørselen vil føre til at den kortsiktige prisveksten på metallene blir høyere enn de modellerte prisøkningene.

Teknologisk utvikling i gruvedrift, resirkulering av kobolt og litium fra elbilbatteriet og ferdigstillelse av nye gruver etter 2022, er faktorer som fører til positivt skift i tilbudskurven og gjør kurven mer elastisk. Utvikling i batteriteknologi vil redusere mengden kobolt og litium i batteriet. Dette resulterer i at økt etterspørsel etter elbiler har en mindre innvirkning på etterspørselen etter metallene. Disse dynamikkene vil i samspill føre til at prisen på kobolt og litium på sikt vil stabiliseres på et lavere nivå enn de observerte prisene i desember 2017.

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1 Introduction

The international ambition to reduce CO_2 emissions is the main reason why the number of electric vehicles worldwide is expected to soar from 3 million today to 530 million by 2040 (Bloomberg New Energy Finance, 2017b). This will result in an electric vehicle revolution.

Currently, electric vehicles are powered by lithium-ion batteries. Cobalt and lithium are two crucial metals used in these batteries. A great increase in demand for electric vehicles is therefore expected to increase the demand for these metals substantially. The central question is whether the increased demand will drive the prices of cobalt and lithium even higher. Alternatively, increasing demand can trigger production increases and improvements in battery and recycling technology. This can potentially counteract the effect of increased demand on the metal prices. Thus, the aim of this thesis is to investigate how increased demand for electric vehicles will influence the price and production of cobalt and lithium.

In order to answer the fundamental question that we raise in this thesis it is necessary to understand several factors that we find will affect the price and production development of cobalt and lithium. This includes mapping the dimension of electric vehicle demand, the current and future battery technology, the role of secondary supply, and present and future actions by metal extraction countries and companies. Only when having basic fundamental information on these factors is it possible to discuss the long-run development in the price of cobalt and lithium.

To answer the research question simplified structural demand and supply models are estimated on reduced form to obtain the covariation between the metal prices and electric vehicle sales. We apply the information of the fundamental factors to discuss whether the relationship between the metal prices and electric vehicle sales remains stable over time. This practical approach is advantageous for integrating the several factors that, in interaction, will affect the price and production of cobalt and lithium.

We predict the likely price development of cobalt and lithium both in the short and long run, where the former covers the period of 2018 through 2022 and the latter, 2023 through 2040. The analysis is based on a low and high demand scenario, with a predicted electric vehicle stock in 2040 of 176 and 530 million, respectively (Morgan Stanley, 2017; Bloomberg New Energy Finance, 2017b).

This thesis focuses on demand for and supply of cobalt and lithium since, as it has been debated in media, these metals could constitute potential bottlenecks for adopting electric vehicles. As electric vehicles are a topic of interest for the general public, the hope is that our approach is easily understood. The electric vehicle is a relatively new demand driver for cobalt and lithium. As such, its effect on the price and production of these metals is still uncertain and the area of research still young. Therefore, there is a continuous need for new research and our goal is for this thesis to be a valuable addition to the existing literature within this topic.

The first part of this thesis covers the current debate regarding cobalt and lithium as potential bottlenecks in the electric vehicle revolution. The following section briefly explains why an electric vehicle adoption is expected and what possible substitutes for the electric vehicle exist. Subsequently, forecasts of the electric vehicle stock are provided. This is followed by a chapter on the lithium-ion batteries. Here current technologies are presented along with an insight into the amount of cobalt and lithium needed in one electric vehicle and their input costs in the battery. New battery technologies under development are also discussed. Subsequent chapters, give an overview of the lithium and cobalt market, highlighting top producing companies and countries, as well as historical price and production development. The final chapter covers our analysis. We first present the method and the data used to predict the price of cobalt and lithium. Descriptive statistics and the price development in the sample period are also given. Thereafter, our results are provided and discussed before we offer some concluding remarks.

2 The ongoing debate about the availability of cobalt and lithium for the electric vehicle revolution

Uncertainty regarding future availability of metals for the electric vehicle technology has led to soaring prices of both cobalt and lithium. From January until December 2017, the price of cobalt more than doubled, reaching 75 205 USD per tonne (Thomson Reuters Datastream). The global average lithium price experienced a similar increase, when from January 2016 until December 2017 the price increased from approximately 8 000 USD per tonne lithium to 16 000 USD per tonne (Miller, 2018). The price increases are either interpreted as signs of future scarcity or simply bubbles about to burst. Although the price of both cobalt and lithium has increased substantially, researchers and market insiders disagree on whether the price growth will continue.

There are several uncertain factors that can have an impact on the future demand and supply of cobalt and lithium. The reason why there are different predictions about future availability of lithium for electric vehicles, is because various assumptions are applied to uncertain factors (Speirs et al., 2014). Speirs et al. (2014) explain that the uncertain factors which require assumptions are; the size of the future electric vehicle stock, the time at which the electric vehicle stock is expected to evolve, the capacity of the future batteries, the amount of lithium in these batteries, the size of the reserves and the production- and recycling rates. The same uncertainties arise when evaluating cobalt as the potential bottleneck for future electric vehicles.

Several studies have focused on the geological availability of cobalt and lithium when evaluating whether they could constitute barriers for the electric vehicle adoption. Some of these studies have found the size of the reserves to be a likely constraint. If there is a rapid increase in electric vehicles, Reuter et al. (2014) find that by 2043 the cobalt reserves may be drained which could potentially result in a considerably higher price of cobalt. A similar study was conducted by Weil et al. (2018), estimating that demand for both cobalt and lithium will exceed the current reserves by 2050. However, there are other studies that draw the opposite conclusion. Based on electric vehicle estimates from the International Energy Agency, researchers at the Öko-Institut (2017) predict that the global reserves of lithium, cobalt, nickel, graphite, and platinum are more than adequate to cover the need for the projected electric vehicle fleet. Narins (2017) expects that the price of lithium will decrease in the long term due to the knowledge of sufficient reserves. Likewise, Glencore's[1] reluctance to enter the lithium market is partly explained by the great amounts of the metal (Lewis & Keidan, 2017).

Even if the reserves were to be strained, estimated resources exceed reserves for both cobalt and lithium and the resources could potentially be utilized (U.S. Geological Survey, 2018). Were all vehicles to be electric by 2087, Gruber et al. (2011) find that these lithium resources will be able to meet the lithium demand. Furthermore, the lithium resource may be higher than estimated as the resource is currently explored to a limited degree (Olivetti et al., 2017; Speirs et al., 2014).

Resources and reserves for lithium and cobalt are not the only uncertain factor, as metals can be reused. And so, the opposing opinions of cobalt and lithium as potential bottlenecks in the electric vehicle revolution must be partly explained by uncertainties regarding factors other than geological availability. Therefore, the predictions of whether cobalt and lithium could constitute hinders for the electric vehicle move beyond the investigations of reserves (Vikström et al., 2013). There is a lack of consensus between market analysts and researchers on whether metal production will be able to meet the metal need as the demand for electric vehicles increase.

Several studies predict that there will be insufficient supply of cobalt and/or lithium to meet the future demand. Vikström et al. (2013) examine different estimated annual production rates of lithium in comparison with rising demand from electric vehicles. They conclude that the annual lithium demand will exceed the estimated production by 2021. Based on annual electric vehicle sales of 11 million in 2025, greater than those applied by Vikström et al. (2013), Morningstar predicts that lithium demand will increase by 16 percent per annum, leading to a supply shortage by 2025 (Holmes, 2017). Olivetti et al. (2017) studied both cobalt and lithium and found cobalt to be the most likely bottleneck for electric vehicle adoption. Based on an estimated annual electric vehicle sale of 10 million in 2025, the cobalt demand will outpace supply by 2025. Supporting Olivetti et al.'s (2017) findings, Benchmark Mineral Intelligence predict that the cobalt market is likely to experience an inadequate supply already by 2021 (Bloomberg New Energy Finance, 2017a). Additionally, Palisade Research (2016)

[1] A major commodity producer.

projects a continuing supply shortage of cobalt that might lead to a doubling of the price from 2016 levels by 2021.

While the previously mentioned researchers find a future supply deficit for cobalt and/or lithium, other analysts foresee a more optimistic future. The belief is that the market "will rise to meet the challenge" (Sanderson, 2017f) of increased demand from electric vehicles. It is a question of understanding the magnitude of the coming demand and adapting thereafter (Sanderson, 2017f). As Biesheuvel et al. (2017) describe the situation for lithium "There's plenty in the ground to meet the needs of an electric car future, but not enough mines". The statement by Biesheuvel et al. seem to be in line with the findings from Öko-Institut (2017). The latter predicts short-term supply deficits for cobalt and lithium, partly because developing a new mine takes time. Bloomberg New Energy Finance (2017a) draw a similar conclusion for cobalt, suggesting that a long run supply deficit can be prevented by additional mines. Whereas Martin et al. (2017) find that the increased lithium demand caused by 9 million registered electric vehicles in 2020 can be met by the supply from projects with completion date the same year. The predictions by analysts at Morgan Stanley are even more optimistic. They predict that the capacity increases and projects in the lithium market will lead to a situation of excess supply by 2019 (Sanderson, 2018a). These findings can be interpreted as a lithium industry well on its way to adapting to the changing market conditions.

However, the above analyses claiming sufficient supply are questioned. Tertzakian (2017) compares the transition to electric vehicles with the mainstream adoption of the internal combustion engines. While the latter had a supply chain for oil in place, the former still needs great expansions of the lithium supply chain to be able to provide the growing electric vehicle market with an adequate supply. According to Mordant (2018) predictions of sufficient lithium supply undervalue the dimension of future demand. While new lithium miners are entering the market, extraction is more challenging than the entrants had foreseen, which has made investors sceptic to provide the needed capital to increase supply (Lombrana & Gilbert, 2017). Another concern posed by Habib et al. (2016) is the concentration of lithium reserves in few countries, which could add to the supply risk. However, Olivetti et al. (2017) and Speirs et al. (2014) oppose the latter view and find lithium production to be sufficiently spread geographically.

There are two pressing issues most researchers and market analysts point to when questioning if the future cobalt need can be fulfilled. The first is the geopolitical supply risk associated with the high dependence on production from the Democratic Republic of Congo. In the 1970s reduced cobalt production in the Democratic Republic of Congo led to a cobalt crisis, resulting in inadequate global supply and vast price increases (Habib et al., 2016; Seddon, 2001). According to Palisade Research (2016), there are no significant cobalt mines in development in other countries and therefore the dependence on the Democratic Republic of Congo will continue. The second concern is how fluctuations in copper and nickel production affects the cobalt supply, as cobalt is a by-product of nickel and copper (Global Energy Metals Corporation, n.d.-b; Palisade Research, 2016).

Despite differing opinions on whether cobalt and lithium will constitute potential bottlenecks in the predicted electric vehicle revolution, their supply chain seems to be reacting to the view that demand will outpace supply. As we will see, investments in new mines are planned, a standardized contract for lithium is suggested, and recycling and substitution possibilities investigated. Moreover, battery and vehicle manufacturers are attempting to secure their supply by different means. For certain, these markets are changing, and these changes will in tandem affect the price and production of cobalt and lithium.

3 Present and future development in the electric vehicle market

This section gives an explanation for why and when an electric vehicle adoption is expected, followed by possible substitutes for the electric vehicle. In addition, the historical development in the electric vehicle stock is provided. The chapter concludes with predictions of the electric vehicle stock conducted by a selection of organizations.

Bloomberg New Energy Finance (2017b) identify five drivers that will intensify the demand for electric vehicles: the short-term governmental backing in market leaders (e.g. US, China, and Europe) and the decreasing battery cost. The growing focus of the auto industry on electric vehicles, the rising consumer interest (due to price competitiveness), and shifting transportation habits.

The International Energy Agency (IEA) defines electric vehicles as battery-electric, plug-in hybrid electric and fuel cell electric passenger light-duty vehicles. Their report "Global EV Outlook 2017" focuses on battery-electric and plug-in hybrid electric vehicles which are referred to as electric vehicles (EVs) (International Energy Agency, 2017). The same categorization and abbreviation will be used in this thesis. Information taken from other sources, without a definition of EVs is assumed to cover the same categories.

3.1 Climate concern - the cause for a possible electric vehicle revolution

In line with the Paris Agreement, the European Commission (2017) proposed that CO_2 emissions from passengers' light duty vehicles should be reduced by 30 percent by 2030, relative to the 2021 level. The suggestion comes with no requirement of EV production, but an encouragement to produce vehicles that are clean in operation. The IEA has calculated how many EVs that are needed to increase the chance of reaching the goals of the Paris agreement by 50 percent. They conclude that EVs will have to account for 60 percent of all passenger vehicles and small trucks by 2060, equivalent to a global stock of 1.2 billion EVs (International Energy Agency, 2017, p. 9).

Several countries have introduced policies to reduce greenhouse gas emissions and put down goals for an increased market share for EVs. According to the IEA, 14 countries had such targets in 2016 (International Energy Agency, 2017, p. 23). Among them are the Netherlands (Muoio, 2017) and Norway (Hegnar, 2017), where it will be allowed to sell only EVs by 2025, followed by India in 2030, and UK and France in 2040 (Muoio, 2017). Although China has not set a specific date, the country is working towards the same goal in the hope of reducing pollution (France-Presse, 2017). However, the Ministry of Industry and Information Technology in China, has stated that "Sales of new energy vehicles should reach 2 million by 2020 and account for more than 20 percent of total vehicle production and sales by 2025" (Reuters, 2017a). According to Clover (2017), the Chinese government has done more than most others to support a growing EV market. The country has selected EVs as one of their strategic industries within their "Made in China" strategy (Clover, 2017; Patterson & Gold, 2018), which outlines a plan to expand and improve the manufacturing sector (Xinhua, 2017). If the goals of these 14 countries from 2016 are met, their stock of EVs combined will grow to 13 million by 2020. An achievable number if the annual growth rates in the EV stock in the years to come resembles that of 2016 (International Energy Agency, 2017, p. 23).

Governmental ambitions of a cleaner transportation sector have driven car manufacturers to set ambitious goals and promise large investments. The Chief executive at Volvo believes that the risk of keeping to the internal combustion engine is greater than the risk related to EV investments. Thus, Volvo will only introduce EVs from 2019 and onwards (Ewing, 2017a). Volvo is one of several examples. Based on vehicle manufacturers' sales targets, the IEA has calculated that the EV stock could reach as high as 20 million by 2020 (International Energy Agency, 2017, p. 24).

3.2 When is the electric vehicle expected to be price competitive with the internal combustion engine vehicle?

Since the EV is not price competitive with the internal combustion engine vehicle (ICE), short run incentives are important to boost both consumer approval and R&D so that the EV can keep and increase its market share in the transportation sector (Norsk elbilforening, n.d.). Several institutions have made predictions of when the EV is expected to be price competitive with the ICE. The date varies by institution and whether the perspective is global or country based. Bloomberg New Energy Finance (2017b) have estimated that it will not be until 2025 without subsidies in a global perspective, whereas the IEA forecasts that it will not happen until 2030 in Europe (International Energy Agency, 2017, p. 20). However, the UBS finds that China will be able to reach price competitiveness already by 2023 (Winton, 2017). China being the first country to reach price competitiveness is not surprising. The country is securing inputs for their EVs like no other, investing in the whole battery chain and providing the EV industry with large subsidies (Patterson & Gold, 2018).

3.3 What are the substitutes for the electric vehicle?

Currently, the ICE and the hydrogen powered vehicle are considered to be substitutes for EVs. Unless the ICE is fueled with biodiesel from renewable sources, it cannot be considered a clean substitute (Statens vegvesen, n.d.). Hence, if the ambition is an improved environment we will assume that the ICE vehicle is not a substitute for the EV. The hydrogen vehicle, similarly to the EV is clean in operation (Durbin, 2017). Therefore we will categorize the hydrogen vehicle as a substitute for the EV in this thesis. While lithium-ion batteries are used in some hydrogen vehicles as well, these are considerably smaller than those utilized in EVs. For example, Mercedes Benz's production ready hydrogen powered vehicle has a 9 kWh lithium-ion battery (Galeon, 2017). Since the battery capacity is lower, and thus contains less cobalt and lithium, we will assume that hydrogen powered vehicles will not affect the price and production of lithium and cobalt.

Consumers will purchase a hydrogen vehicle if it is considered to be the best option. Currently it is not. Demand for hydrogen vehicles has been low, partly because the infrastructure for fuelling is unsatisfactory. Great investments would have to be put towards building the fuelling stations before the hydrogen vehicle can become the preferred choice for the vast majority. However, the incentive to do so has been low, since the demand for the hydrogen vehicles have been lacking. Furthermore, manufacturers will not produce vehicles there is little demand for (Durbin, 2017).

3.4 Growth in the global electric vehicle stock, 2005-2017

Despite the fact that EVs are not price competitive with the ICE, the global EV stock has increased from 1 370 EVs in 2005 to 2 million in 2016 (International Energy Agency, 2017, p. 52). The EV sales in 2017 were approximately 1.2 million, leading to a global EV stock exceeding three million (Inside EVs, n.d.). Figure 1 shows the exponential growth in the EV stock from 2005 until 2017. Between 2015 and 2017 the annual average growth rate of the EV stock was 60 percent. However, of the total number of passenger and small truck vehicles the EVs accounted for a mere 0.2 percent in 2016 (International Energy Agency, 2017, p.6).

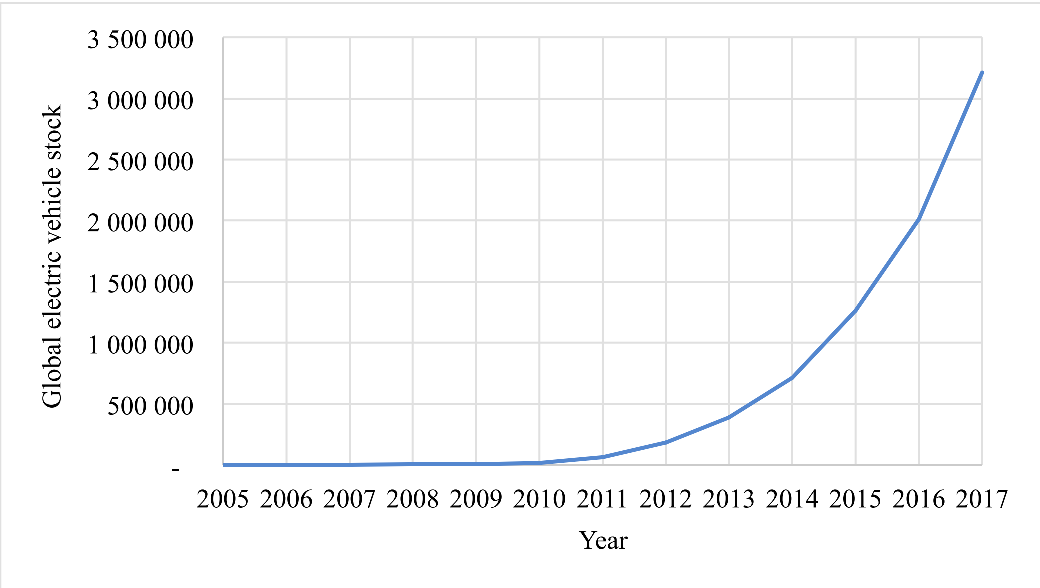

Figure 1 *The global electric vehicle stock, 2005-2017.* ***Source****: Data on the electric vehicle stock, 2005-2016 from the International Energy Agency (2017, p. 49). Electric vehicle sales in 2017 from Inside EVs (n.d.).*

3.5 Predicted electric vehicle stock in 2040

As a result of expected increased demand for EVs several organisations have attempted to forecast the EV stock in coming years. Even though they share an increasing trend, the estimates vary. Predicting the EV stock is beyond the scope of this thesis. Instead forecasts provided by two organizations will be applied as estimates for the increased demand for EVs. These will be used when analysing the likely price and production development for cobalt and lithium. Since the influence of EVs on the price and production of cobalt and lithium will vary depending on the predicted EV stock, we have chosen two scenarios, which we categorize as low and high demand for EVs. This thesis will be based on the forecasted EV stock of one billion EVs in 2050 conducted by Morgan Stanley (2017) and Bloomberg New Energy Finance's (2017b) estimated EV stock of 530 million in 2040. Morgan Stanley and Bloomberg New Energy Finance's predictions will be referred to as low demand scenario and high demand scenario, respectively.

The forecasts of the EV stock in different years have been used to calculate a corresponding compounded annual growth rate (CAGR), these proxies the annual growth rate in EV sales. All predicted growth rates are lower than the observed growth rates during the last 10 years. To be able to compare the predicted EV stocks we have assumed that the current EV stock will increase with the CAGR corresponding to Morgan Stanley's prediction until 2040. With the CAGR corresponding to Morgan Stanley's projection, the EV stock will reach approximately 176 million in 2040. The latter estimate differs considerably from Bloomberg New Energy Finance's. The growth rates in EV sales in the low and high demand scenario are given in table 1. To illustrate the difference between the scenarios further the development in the electric vehicle stock is shown in figure 2. As we move forward in time, the difference between the electric vehicle stock in the low and high demand scenario becomes greater.

Table 1 *Annual growth rate in electric vehicle sales until 2040, low and high demand scenario.*

	Low demand scenario Morgan Stanley	**High demand scenario** Bloomberg New Energy Finance
Electric vehicle stock in 2040	176 million	530 million
Annual growth rate electric vehicle sales	19 %	25 %

Source: *Morgan Stanley (2017) and Bloomberg New Energy Finance (2017b).*

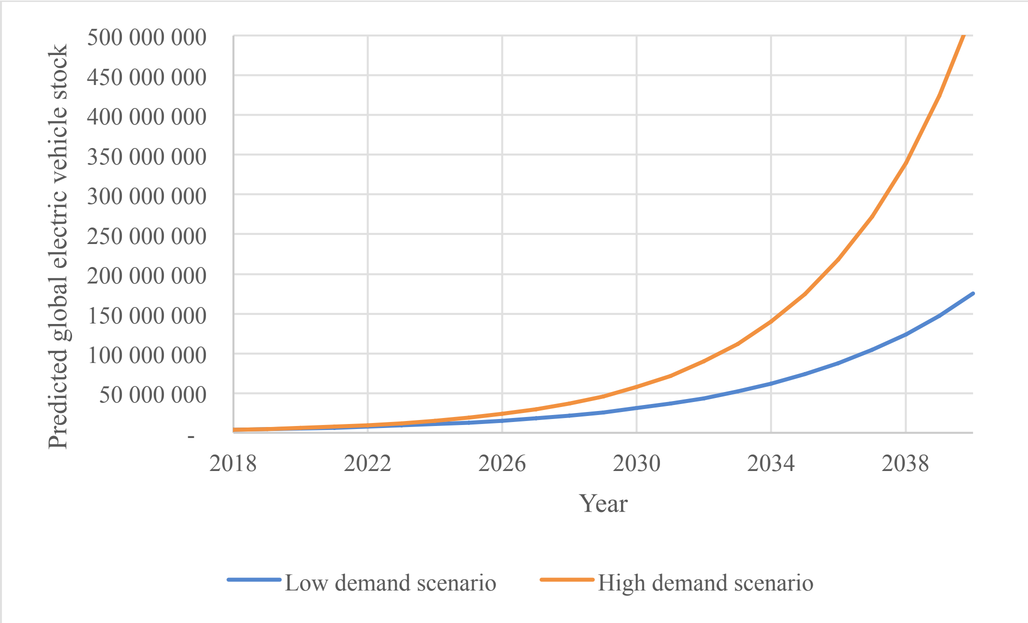

Figure 2 *The predicted global electric vehicle stock, 2018-2040. Low and high demand scenario.* ***Source:*** *Morgan Stanley (2017) and Bloomberg New Energy Finance (2017b).*

4 Lithium-ion batteries – current technologies, input costs and possible developments in the battery technology

Over the last decade lithium-ion batteries have become the dominating technology in EVs. Lithium-ion battery is a general term that covers rechargeable batteries containing lithium-ions (Valmot, 2013) and the lithium-ion battery will henceforth be referred to as a LIB. Since cobalt and lithium are used in the LIBs, these batteries are the connection between the metals and the EV. In order to answer the fundamental question that we raise in this thesis i.e. how will increased demand for electric vehicles influence the price and production of cobalt and lithium, it is necessary to understand the linkage between the EV and these metals. Since battery technology is beyond our field of expertise factual errors may occur. Furthermore, the chapter is an introduction, thereupon someone familiar with the subject, is advised to proceed to the next chapter.

First, some of the characteristics of cobalt and lithium are briefly mentioned. Followed by a description of the composition of the LIB and the characteristics that make the LIBs popular in EVs. Approximations of the amount of cobalt and lithium needed in one EV along with an estimate of the metals input cost in a LIB, is also provided. Past improvements in the LIB technology as well as future technologies are presented. The latter focuses on possible substitutes for cobalt and lithium. The chapter concludes with information regarding recycling of cobalt and lithium from LIBs.

4.1 A primer on lithium and cobalt

Lithium (Li) has atomic number three in the periodic table and is lighter than any other metal. Lithium leads electricity at a high rate and this metallic element can easily form positive ions (Pedersen, 2018). While there are several types of lithium compounds, lithium carbonate, lithium hydroxide, and lithium oxide are the most common (British Geological Survey, 2016). The different compounds have various end-uses, such as batteries, ceramics, glasses, and greases. However, lithium carbonate or lithium hydroxide are often used in LIBs (Miller, 2018). In this thesis lithium will cover all variations of lithium compounds unless otherwise stated.

Cobalt (Co) is a hard, silver-white metal, with atomic number 27 in the periodic table (Kofstad & Haraldsen, 2017). Cobalt leads heat and electricity at a low rate and can easily form alloys. Moreover, at high temperatures cobalt preserves its characteristics, which are strength and magnetism (British Geological Survey, 2009). LIBs and superalloys are the two main uses for cobalt (Global Energy Metals Corporation, n.d.-a). Cobalt is used in LIBs because it provides the battery with stability and enables a fast recharge process (Perks, 2016; Reuters, 2018a). While there are several cobalt compounds, cobalt sulphate is the most common compound used in LIBs (Desai, 2017).

4.2 Components in the lithium-ion battery, its characteristic and past development in the battery technology

The components in a LIB are easily explained by UngEnergi (2017), therefore their information and layout combined with additional sources is used to describe the components in an understandable manner.

A lithium-ion battery consists of the following components:

- The anode in solid form, contains elements which oxidize easily, commonly graphite (Gunvaldsen & Rosvold, 2017).
- The cathode is an electrode in solid form, which contains metal oxides and wants to attract electrons. Here the reduction takes place.
- The separator parts the cathode from the anode and prevents the electrons from moving between the cathode and anode through the electrolyte, therefore short circuits are avoided. The separator only lets through lithium-ions (Rapp, 2015; Valmot, 2013).
- The electrolyte is in liquid form and contains a lithium salt. It leads the lithium-ions between the anode and cathode (Valmot, 2013).
- The two current collectors are metals connected to the anode and cathode, which create contact between these and the outer poles of the battery. Copper is connected to the anode and aluminium to the cathode as these metals lead electrons better than the cathode and anode material (UiO: Kjemisk institutt, 2010).

The cell reaction in the battery in use defines whether the electrode is a cathode or an anode (Valmot, 2013). When the battery is fully charged, there are several electrons in the anode. These electrons are attracted to the positive. The chemical reaction starts when the battery is in use and the electrons moves from the anode to the cathode. In motion they create current. (Gunvaldsen & Rosvold, 2017). As Rapp (2015) explains it, the positively charged lithium-ions travel from the anode to the cathode through an electrolyte via the separator. The electrons go the opposite direction of the definitions of the current (Gunvaldsen & Rosvold, 2017). When charging a LIB, the process is reversed by adding current (Rapp, 2015).

There are several types of LIBs where the chemical composition in the cathode differs. The batteries are named after these materials (Valmot, 2013). A selection of LIBs along with some of their characteristics are given in table 2 below, based on information and tables provided by the Battery University (2017). Compared to other battery technologies, the LIBs have a high specific energy (Ruud, 2018), meaning that it can run for a long time before it has to be recharged (Battery University, 2017). The specific energy in the LIBs typically range between 85-250 Wh/kg (Valmot, 2013). Additionally, the LIBs have a high energy conversion efficiency, approximately 95 percent of energy supplied to the battery can be reused (Valmot, 2013). Moreover, the battery has no memory effect (UiO: Kjemisk institutt, 2010) and when it is not in use the battery discharges at a slow rate (Gunvaldesen & Rosvold, 2017; Valmot, 2013) These characteristics make the LIB a preferred technology for EVs and other electronic devices.

***Table 2** Types of lithium-ion batteries.*

	Lithium cobalt oxide	**Lithium manganese oxide**	**Lithium nickel manganese cobalt oxide**	**Lithium nickel cobalt aluminium oxide**
Abbreviation	LCO	LMO	NMC	NCA
Chemical symbol	$LiCoO_2$	$LiMn_2O_4$	$LiNiMnCoO_2$	$LiNiCoAlO_2$
Year of introduction	1991	1996	2008	1999
Anode	Graphite.	Graphite. Silicon is sometimes included to improve capacity.	Graphite. Small amounts of silicon is sometimes added, similarly to the LMO.	Graphite.
Cathode	Lithium cobalt oxide. Contains 60 % cobalt.	Lithium manganese oxide.	Lithium nickel manganese cobalt oxide. Contains 10-20 % cobalt*.	Lithium nickel cobalt aluminium oxide. Contains 9 % cobalt.
Specific energy	150-200 Wh/kg, special cases: 240 Wh/kg.	100-150 Wh/kg.	150-220 Wh/kg.	200-260 Wh/kg.
Applications	Mobile phones, tablets, laptops and cameras.	Power tools, medical devices. Formerly used in EVs.	E-bikes, medical devices and EVs.	Medical devices, and EVs.

***Source**: Battery University (2017) and * Cobalt Institute (n.d.).*

The following will explain how the cathode materials in LIBs have developed over time. Unless otherwise stated, the information is based on Nitta et al's. (2015) research regarding lithium-ion battery materials and information by the Battery University (2017). The LCO, introduced by SONY, is the most common LIB. While the LCO has high specific energy and low self-discharge, its power to weight ratio (specific power) is low, meaning that such a battery with high power will be heavy. In addition, the battery has a short life span and if the cathode material is exposed to excessive heating, it is flammable. The latter describes the property low thermal stability. As we can see in the table, the LCO cathode has a high share of cobalt, which makes the battery costly.

Following the introduction of the LCO, the technology has continued to develop. To improve the lifespan, specific power, and cost, newer cathode materials therefore include nickel, manganese, and aluminium. The LNO (Lithium Nickel Oxide) was introduced to the market, but due to issues with the chemical composition in the cathode the battery was unsuccessful. The NCA cathode was a result of partial substitution of nickel with cobalt and the addition of aluminium, which provides stability. The NCA battery has a long lifespan, high specific energy, and specific power. To reduce the cost and toxicity of the NCA battery, cobalt and nickel were replaced with the inexpensive metal manganese, resulting in the LMO and NMO (Lithium Nickel Manganese Oxide) cathodes. Currently the NCA and NMC cathodes are most prevalent in EVs. The NMC chemistry is quite similar to the LCO cathode, however, the unfavorable qualities of the LCO have been improved. The NMC has equal or higher specific energy compared to the LCO, and since the share of cobalt is lower the cathode material is less expensive. Today, the ratio of nickel, manganese and cobalt in the NMC cathode is usually equal, however research has enabled a 39 percent reduction of both manganese and cobalt (Jaffe, 2017).

4.3 What is the amount of cobalt and lithium in a lithium-ion battery and to what extent do these metals contribute to the overall battery price?

The exact amount of metals used in different battery technologies for EVs is not known, mainly because manufacturers do not publish the information. The predictions of the price and production development of cobalt and lithium in chapter 6 are therefore based on approximations.

The average of an NMC and NCA battery with different capacities, is used as a proxy when estimating the amount of cobalt and lithium carbonate one EV requires. Currently, Nissan Leaf's NMC battery has a 40 kWh battery capacity. Since an NMC battery contains 0.36 kg cobalt per kWh (Gandon, 2017), the 40 kWh NMC battery holds 14.4 kg of cobalt. A previous technology in Nissan Leaf is used when estimating how much lithium is needed in a 40 kWh battery. This NMC battery contains 36 kg lithium carbonate (Valle, 2016b). As a starting point to find the amount of cobalt and lithium carbonate that is used in one NCA battery, Tesla Model S with a battery capacity of 70 kWh is used as an estimate. Tesla batteries contain 0.22 kg cobalt per kWh (Gandon, 2017), thus a Model S with a capacity of

70 kWh holds 15.4 kg of cobalt. The amount of lithium is approximately 63 kg lithium carbonate (Lambert, 2016). Henceforth, it is assumed that future EVs will use an average of these two battery capacities, i.e. a 55 kWh battery will contain 14.9 kg of cobalt and 49.5 kg of lithium carbonate.

Although the demand for EVs is expected to increase, there are still obstacles before EVs are likely to be adopted by the vast majority. One of these hinders is the battery price, which currently prevents the EV from competing with the ICE on price (Watanabe, 2017). In 2016, 50 percent of the EV cost could be explained by the battery. To put this in a perspective, in order for the EV to be competitive, the cost of the LIB needs to be halved (Watanabe, 2017). The price of a LIB was approximately 273 USD per kWh in 2016 (Curry, 2017), resulting in a total price for a 55 kWh battery of 15 015 USD. Of these costs, cobalt and lithium accounted for 13 percent, at prices from December 2017.

The development of the battery technology exhibits that there has been a focus on reducing the amount of cobalt partly because cobalt is an expensive metal. However, according to Bloomberg New Energy Finance (2017a), cobalt is currently not a great contributor to the overall battery price. The price of a battery with NMC chemistry will rise by 13 percent if the cobalt price should increase by 400 percent. Furthermore, the EV price is barely affected by the increased cobalt price. When investigating how the price of lithium affects the price of different LIBs, Ciez and Whitacre (2016) find similar results as Bloomberg New Energy Finance does for cobalt. For the battery technologies under examination, the total price of the batteries would increase by less than 10 percent if the lithium price was to threefold.

Considering that the battery price has already been cut in half from 2011 to 2017 (Ewing, 2017b), a further price reduction of the LIB may be difficult. However, the estimate by Morgan Stanley is optimistic, the price of LIBs is likely to decrease by approximately 50 percent by 2020 (Patterson & Gold, 2018). As the price of batteries decline, the more important the price of the inputs become (Olivetti et al., 2017). The previous price decline of LIBs is a result of economics of scale and technological advancement (Curry, 2017). Increased prices of input factors can counteract further price reductions caused by technology and economies of scale. This can potentially make the battery more expensive and prevent increased demand for EVs which in turn affect the demand for cobalt and lithium.

4.4 What new technologies can represent game shifters for cobalt and lithium demand?

Battery technologies are changing quickly. Looking back, the cathode material has already been altered because of unfavorable qualities. Research has been and still is, focusing on finding cathode materials with high specific energy, improved safety, and reduced rates of cobalt. Finding a perfect substitute for cobalt has not been successful due to the characteristics it provides to the battery. However, partial substitution of cobalt has had better outcomes and the potential for full substitution exists. Within 2027, partial substitution could possibly lead to a 10-20 percent reduction of cobalt in the cathode (Bloomberg New Energy Finance, 2017a). High specific energy cathodes without cobalt are not used in today's EVs, but according to Olivetti et al. (2017) there are several metals that can replace cobalt entirely while maintaining the high specific energy. However, these cathodes are yet to be applied outside the laboratory.

Nowadays, solid-state batteries are a favored research area. One of the advantages of these batteries with solid electrolytes, seems to be improved safety (Berckmans et al., 2017). With conventional LIBs there is a possibility of leakage which can cause fire (Valle, 2017a). According to Olivetti et al. (2017), solid-state batteries might contain more lithium compared to the conventional LIB. Several car manufacturers are planning to use the solid-state technology in their future EVs. Among those are, Toyota who plans to introduce the solid state batteries by 2020 and BMW before 2030 (Lygre, 2017). The adoption of such a technology could lead to additional demand for lithium (Olivetti et al., 2017), and therefore drive the lithium price even higher, ceteris paribus. In addition to the solid-state batteries, the lithium-air batteries can increase the lithium demand (Olivetti et al., 2017). As the name indicates, the lithium-air battery will be light which will be beneficial for the EV (Christensen, 2015). Furthermore, the battery would be able to deliver high specific energy (Ruud, 2018).

In the process of developing the solid-state batteries, researchers have come across solutions that could make it possible to substitute lithium. These are far in the future and still require extensive research to become commercially viable. Attempting to substitute lithium with gold, researchers at the University of California seem to have found promising results. They are now looking to test whether a less expensive metal can replace the gold (Lekanger, 2016).

Whereas a Swiss project is pursuing sodium or magnesium as possible substitutes for lithium. While sodium is less expensive than lithium, it will provide lower specific energy, meaning that such a replacement will come at the expense of the size of the battery. The advantage with replacing lithium with magnesium, is that magnesium-ion can provide higher energy density than the lithium-ion (Remhof, 2017). Furthermore, the research team at the University of Texas, led by one of the inventors of the lithium-ion battery, are working on a solid-state battery where lithium could be replaced by sodium (Thonhaugen, 2017).

As seen, the battery technology is continuously evolving. Consequently, creating uncertainty regarding how much cobalt and lithium future batteries requires. Therefore, to what extent increased demand for EVs will affect the price and production of cobalt and lithium.

4.5 What effect can recycling lithium and cobalt from lithium-ion batteries have on the supply of these metals?

Metals from EV batteries are not recycled to a great extent[2] (Valle, 2016a). However, it is fully possible to recycle both cobalt (Valle, 2017b) and lithium (Elibama, n.d) from LIBs. Therefore, when demand for EVs increase the circumstances may change. The motivation for recycling batteries is to avoid a supply deficit in addition to reducing the need for primary production, CO_2 emissions and reliance on the largest producing countries (Elibama, n.d). However, it is challenging to develop a recycling method that works for all types of LIBs used in EVs (Sanderson, 2017h). Even more, the recycling process will need to be continuously altered as the battery technology develops (Valle, 2016a). Neither Olivetti et al. (2017) nor Vikström et al. (2013) believe that secondary supply will be able to contribute much to supply in the short run. On the basis that batteries have a long lifespan so there is not much available material to recycle. However, by 2025 the recycling industry is believed to be commercialized on a larger scale (Sanderson, 2017h). By that time, Melin (2017) finds that recycled metals from LIBs can add 22 500 tonnes of cobalt and 30 000 tonnes of lithium carbonate to supply.

[2] Most likely, it is possible to recycle lithium and cobalt from other end-use than LIBs, which could increase the availability of the metals. However, we have not taken such possible methods into consideration.

5 An overview of the lithium and cobalt markets

An insight on the lithium and cobalt market is needed in order to evaluate how the predicted EV revolution will affect their prices and production. The following chapter intends to provide such an insight. This includes the major producing companies and countries with special attention given to mine projects in development[3]. The way countries and firms have already responded to the increasing demand gives an idea of the future supply curve. In the long run, changes in the supply curve are equally important as changes in demand to determine the price development. Moreover, the location and size of the reserves and resources are provided to give an impression of how much of these metals are found in nature. Additionally, the historical price development of both metals is explained in the context of factors that are relevant drivers of the price.

The distinction between resources and reserves depends on different variables that can change quickly and often. This makes it difficult to define a deposit as a resource or a reserve. The categorization depends on whether it is profitable to extract the metal, which in turn depends on deposit size, metal content, and extraction methods among other factors. For example, if the price of the metal increases, one may start using poorer deposits, i.e. the deposit changes from a resource to a reserve. (Gruber et al., 2011).

5.1 Lithium – deposits, producers, production, consumption, and historical price development

In this chapter the aim is to provide an overview of the lithium market. Lithium deposits, top producing companies and countries, in a market that have been and still is under changing conditions, are presented. We will see that existing deposits are expanding, new ones utilized, others explored, and extraction technologies are under improvement. These changes can be attributed to an increased demand for batteries.

The market leading lithium extraction companies are SQM, Albemarle, FMC Lithium, Tianqi Lithium, and Jiangxi Ganfeng Lithium. Previously, SQM, FMC Lithium, and Albemarle

[3] When projects are mentioned we are referring to the development and construction of new cobalt and/or lithium mines.

controlled the lithium market; extracting the metal in just a few countries (Kay, 2018b). As a result of increased demand for lithium, new players have entered the market, both producers and countries (Sanderson, 2017a).

5.1.1 Types of lithium deposits and costs of extraction

Lithium deposits can be divided into three types, namely brine, pegmatite, and sedimentary rock (Gruber et al., 2011). These types constitute 66, 28, and 8 percent of the lithium resources, respectively. However, at the present time lithium is only being extracted from pegmatite and brine (British Geological Survey, 2016). Lithium brine is water with a high concentration of lithium salts, found in the pores of rocks after evaporation. Brine is the largest source for lithium, and salt lakes, also known as salt flats or salars, is the most common type of brine deposit (British Geological Survey, 2016; Valle, 2016b). After the lithium brine has evaporated due to sun exposure, lithium carbonate can be obtained by adding sodium carbonate to the salt lakes. Other elements like sodium and calcium can also be recovered in the process (Valle, 2016b). Briefly explained, lithium containing pegmatites are rocks formed by solidification of magma (King, n.d; Raade, 2017). The pegmatites contain minerals in which lithium can be found. The minerals that are most common and profitable to extract are spodumene, lepidolite, and petalite. Elements like tin, tantalum, and niobium can also be extracted from pegmatites. Previously, lithium was often extracted from the ore eucryptite and the mineral amblygonite, however, these sources are no longer economically viable for lithium extraction (British Geological Survey, 2016). Several companies engage in lithium extraction from both brine and pegmatite deposits, with facilities in several countries (Gruber et al., 2011).

The lithium deposits from sedimentary rock are clay and lacustrine. Lithium is found in the mineral hectorite in clay, and in the mineral jadarite in lacustrine (Gruber et al., 2011). According to British Geological Survey (2016), lithium is neither extracted from hectorite nor jadarite, but these minerals are potential candidates for future lithium extraction.

As previously mentioned, the long run supply curve is dependent on the development of projects. However, in the shorter time frame, without defining the lithium market as perfectly competitive, the marginal cost of extraction can give an impression of the supply curve. Depending on source of extraction, the marginal costs differ. Lithium extraction from brine is the less expensive, with a cost of 2 000 to 3 800 USD per tonne of lithium carbonate equivalent (Bohlsen, 2016; Lombrana & Gilbert, 2017). Whereas extraction from spodumene costs between 4 000 and 6 000 USD per tonne of lithium carbonate equivalent (Bell, 2017; Bohlsen, 2016; Lombrana & Gilbert, 2017). The supply curve will remain the same until projects have come into commercial production or technology has improved the method of extraction. It takes approximately five years from exploration of a lithium brine deposit until a new mine is completed (Desjardins, 2015).

Lithium is often reported in various units of measurement which can be a source of confusion. Tonnes of lithium can either be reported as tonnes of brine and mineral, lithium compounds, lithium carbonate equivalent (LCE) or as lithium content. Price, supply, and demand are often reported in LCE (Gordon, 2015). Since lithium is reported in various ways depending on source, we have used the following conversion in this thesis; 1 tonne lithium content is approximately equal to 5.3 tonne of LCE (European Metals Holdings Limited, 2015).

5.1.2 Which countries are the biggest producers of mined lithium?

As we have seen, lithium can be extracted from different types of deposits. These deposits are scattered across the world. The following section will cover major lithium hosting and producing countries.

Chile

The greatest lithium brine deposits are found throughout parts of Chile, Argentina, and Bolivia which has made the area known as the "lithium triangle" (Kay, 2018d).

For several years, Chile has been the global leader in lithium production and the country hosts the largest brine producing deposit, Salar de Atacama (Gruber et al., 2011; Kay, 2018d). Both SQM and Albemarle are allowed to extract lithium from this salar under production quotas (Kay, 2018b). Although Chile has the lowest cost of extraction compared to any other country, it has not been able to take advantage of the increased demand for the metal (Wahlberg, 2018), making Chile the second largest producer of lithium (Kay, 2018c).

Political conflicts, corruption, and disagreements regarding the resource explain Chile's failure to increase production. Moreover, lithium has been categorized as a strategic mineral by the Chilean government. While the law has been beneficial for the environment in the desert, it is among the factors that has hindered increased production (The Economist, 2017). Another factor that has stalled production increases in Chile is SQM's long-running conflict with the Chilean economic development agency, Corfo. The latter, who regulates the lithium reserves, has accused SQM of not paying the lease of the land in the Salar de Atacama. Therefore, Corfo has denied to raise SQM's quotas. Without an increased quota, the company would have reached its production limit in 2022 (Choen, 2018). However, it appears that the situation in Chile is about to change as Corfo and SQM came to a resolution early 2018 (Sanderson, 2018b). The company has now been permitted to fourfold its production by 2026 (Sanderson, 2018b) under certain conditions (Iturrieta, 2018b). With the additional quotas, SQM can deliver 216 000 tonnes of LCE per year to the lithium market (Iturrieta, 2018b). According to Iturrieta (2018a), Tesla and SQM are discussing an agreement which involves SQM providing Tesla with lithium brine. The Chilean government is therefore considering to further increase SQM's production quotas.

Besides increasing SQM's quotas, Corfo raised Albemarle's quotas in the Salar de Atacama beginning 2017 (Sanderson, 2017b). By September 2017, the company called for an additional increase to 125 000 tonnes of LCE annually, due to a new technology that could make it possible to produce more lithium without extracting more brine (Albemarle Corporation, 2017). In March 2018, Corfo granted Albemarle the increased quotas, permitting an annual production of 145 000 tonnes of LCE until 2043. The technology is expected to be used by 2021 (Albemarle Corporation, 2018).

Argentina

Argentina, the third largest lithium extracting country, has several deposits and the ambition of becoming the leading South American producer. The president is facilitating this goal with new regulations, such as the removal of the export tax on metals, to open the mining industry for foreign investments. As a result, several foreign investors are launching projects in Argentina. Among them are SQM and Lithium Americas who will start production in Argentina by 2019 through a joint venture. Moreover, Orocobre, which is currently operating in the Salar de Olaroz, will also be increasing its production by 2019 in the country. The great investments have led to projections of a fourfold in lithium exports from Argentina. (Castilla, 2017).

Bolivia

Like Chile, Bolivia has struggled to increase production of lithium in response to increased demand. Although Bolivia hosts the world's largest lithium brine deposit, rain and other natural challenges have dampened production. As global demand for lithium increases, Bolivia aspires to attract foreign investors like it has in the neighbouring country. However, it is more challenging to extract lithium from the Bolivian deposits due to the high magnesium content. (Alper, 2017). Therefore, some investors have been sceptical to invest in the country, as they find the Bolivian lithium to be unsuitable for LIBs (Sanderson, 2017e). In addition to previously being quite closed off to foreign investors and having an unfavorable lithium quality, the country has a weak infrastructure system. This has limited lithium production in Bolivia compared to the remaining countries in the "lithium triangle" (Narins, 2017).

The benefit of increased production in the "lithium triangle" comes at the expense of the indigenous people living in the desert and their communities. However, a large percentage of the employees in the salars are indigenous people who would otherwise be unemployed. On the other hand, this area already has water shortage and increased production would make this problem more severe (Frankel & Whoriskey, 2016).

Australia

Australia is the global leader of lithium production (Kay, 2018c). As oppose to the "lithium triangle", Australian lithium extraction is from hard rock. According to Stringer (2017b), Greenbushes in Australia is the world's largest producing pegmatite mine. The mine is owned by Talison Lithium, a company controlled by Tianqi Lithium and Albemarle (Kay, 2018b). Extraction companies operating in Australia, for example Talison Lithium is also responding to the increased lithium price. The company declared plans to increase their mine capacity by a minimum of 100 percent in 2017 (McKinnon, 2017).

Western Australia possesses great amounts of the metals used in batteries, therefore the region has been appealing to international investors. The area has several lithium producing mines and more projects in development (Smyth, 2017). Among these projects are the Wodgina mine deposit owned by Mineral Resources Ltd., which contains the greatest hard rock lithium resource in the world. The advantage of the largest projects in Western Australia, with planned start-up in 2018, is their strategic location close to the seaport city of Port Hedland (Stringer, 2017a). Australia can keep its position as the global leader if these projects come into commercial production as planned, supplying 37 percent of the global total in 2027 (Stringer, 2017a).

China

China was the fourth largest lithium extracting country in 2017 (Kay, 2018c) and is exceeding all other countries in the run to secure lithium supply (Meredith, 2017). While China possesses 13 percent of global lithium resources, domestic production has not been significant in the recent years (U.S. Geological Survey, 2018). China has had a low production because they have drained lithium from existing mines and because the remaining resources are located at unfavourable altitudes. Furthermore, large parts of the country's resources have a poor chemical composition (Lithium Today, 2017). Additionally, the lithium extraction that has been initiated and approved by the government, have inflicted negative externalities on the environment (Free Tibet, n.d). Therefore, the Chinese government has encouraged Chinese lithium companies to pursue resources abroad (Shane, 2017). The Chinese company, Jiangxi Ganfeng Lithium is the country's second largest lithium producer and has successfully invested in projects and mines outside of China. The company has, through a joint venture with Albemarle and SQM, plans to expand lithium production in Argentina. Furthermore, Jiangxi Ganfeng Lithium also holds stakes in an Australian mining company (Benton, 2017).

Other countries with lithium deposits

Currently there is no large scale production of lithium in Europe (European Lithium, n.d). However, there are projects both in the Czech Republic and Serbia. Cinovec in the Czech Republic, previously known for its tin production, plans to take advantage of its lithium resources. The Czech government has signed an agreement with European Metals, an Australian mining company, to pursue a possible lithium project (Shottr, 2017). The European Metals (n.d) claim that lithium extraction from the deposit in Cinovec can be performed at the lowest cost, globally. Additionally, the Cinovec deposit has an advantageous location close to the remaining lithium-ion battery supply chain in the centre of Europe (European Metals, n.d). As previously mentioned, lithium is currently not extracted from jadarite or hectorite. However, increased lithium demand seems to have made these sources relevant. There is a project in the Jadar deposit, in Serbia owned by Rio Tinto. If this project was to come into commercial production, it could cover 10 percent of the global lithium need (Rio Tinto, n.d). Similarly, Lithium Americas Corporation is exploring whether they can economically extract lithium from hectorite (Lithium Americas Corp., 2017).

5.1.3 The size and location of the lithium reserves and identified resources

The U.S. Geological Survey (USGS) estimated the global lithium reserves were 16 million tonnes of lithium content in 2017, whereas the identified resources were estimated to be 53 million tonnes. From 2016 to 2017, global identified resources increased by 13 percent. The increase can perhaps be explained by the lithium producers continued exploration for new projects. Chile's reserves, at 7.5 million tonnes of lithium content, are double that of any other country and constitute almost half of the global total. Together the countries in the "lithium triangle" host over half of the world's identified resources. Argentina has the highest estimated identified resources of 9.8 million tonnes of lithium content. (U.S. Geological Survey, 2017c; U.S. Geological Survey, 2018). The European Metals claim that Cinovec, in the Czech Republic, has the largest identified lithium resources in Europe of 1.3 million tonnes of lithium content (European Metals, n.d).

5.1.4 How has lithium consumption and production developed from 2009-2017?

Data on lithium consumption is originally collected by Roskill and we have obtained the data from the secondary source, Hykawy and Chudnovsky (2017). The calculations on lithium consumption are based on these data. The consumption and production development are shown in figure 3. Total lithium demand has increased with a yearly average of 11 percent from 2009 to 2016. However, demand for lithium in different applications has not evolved equally. From 2009 to 2016 the average yearly increase in lithium demand for batteries was 18 percent, compared to 9 percent for other applications. The expanding markets for EVs and other electronic devices have driven the substantial growth in lithium consumption for batteries (U.S. Geological Survey, 2018). The most likely explanation for the increased lithium demand for batteries, especially from 2015, is the governmental backing of the EV industry in China. Besides, Japan increased consumption in 2015, mainly because of Tesla's increased need for batteries produced by Panasonic (U.S. Geological Survey, 2017b).

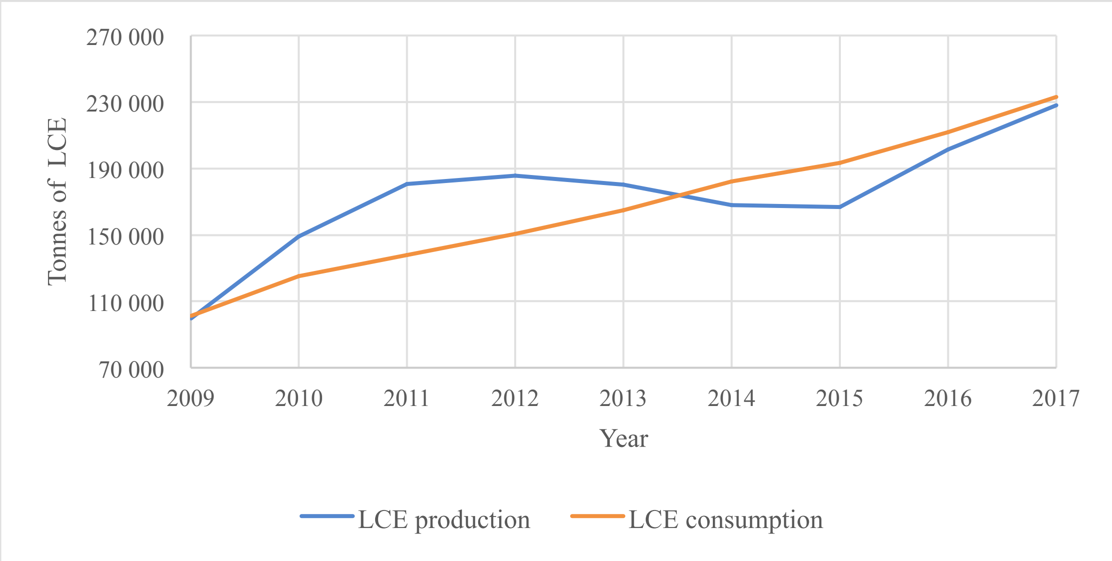

Figure 3 *Lithium production and consumption in tonnes of lithium carbonate equivalent (LCE), 2009-2017.* ***Source:*** *Data on production is collected from USGS's 2010-2018 "Mineral Commodities Summaries" and converted to LCE. Data on consumption is provided by Hykawy and Chudnovsky (2017).*

USGS reports lithium production in their annual "Mineral Commodity Summaries 201x" and the data on production is collected from the summaries 2010-2018. The data is used as a basis for the calculations below. Production, recycled material and inventories constitute the global supply of lithium. Because data on secondary supply, and inventories is unavailable, production is used as an estimate of total supply. Figure 3 shows the production development from 2009 until 2017. Starting with a period of increasing production until 2012, with an average yearly increase of 24 percent, a three-year period of declining production followed. Thereafter a new boost came in 2015. The drop from 2012 to 2015 resulted in an average yearly decrease of 3 percent.

Despite FMC's capacity increase in Argentina in 2013, challenging weather conditions lowered the country's production (U.S. Geological Survey, 2015a). Between 2014 and 2015, the largest producer of lithium at the time, Chile, reduced its production by 9 percent (U.S. Geological Survey, 2017b). The Chilean production was halted by excessive rainfall in 2015 which lead to a short-term shutdown of SQM's extraction in the Salar de Atacama (U.S. Geological Survey, 2017b). These events are believed to be the reason for the decline in production between 2012 and 2015.

Following 2015, the production increased with a yearly average of 17 percent. Both Australia and Argentina expanded their lithium extraction in 2015 (U.S. Geological Survey, 2017b). A new brine deposit, Salar de Olaroz, entering production yearend 2015 (Orocobre, n.d), might have accounted for Argentina's increase. The effect of this new brine deposit could partly explain the production increase of 58 percent during 2016 in Argentina. Additionally, Albemarle was authorized to increase lithium extraction from the Salar de Atacama in Chile. According to Desai and Shabalala (2017) FMC increased its lithium hydroxide capacity with 80 percent the following year.

5.1.5 Historical price development for lithium, 2005-2016

Lithium is not traded on any exchange, thus there is no standardized price for lithium. The price is determined through private agreements between producers and consumers. As a respons to the increased demand for lithium, the London Metal Exchange (LME) might initiate a lithium contract. However, the storing of lithium makes such a contract problematic. The issue arises because the lithium compounds are stored as chemical powders (Sanderson, 2017g) which in contact with water can be flammable (University of Michigan-Flint, 2014).

Benchmark Mineral Intelligence track the lithium price and reports it in lithium carbonate and lithium hydroxide. Figure 4, taken from Energy and Capital (Kohl, 2016) where the primary source is Benchmark Mineral Intelligence, will be used when analysing the price development.

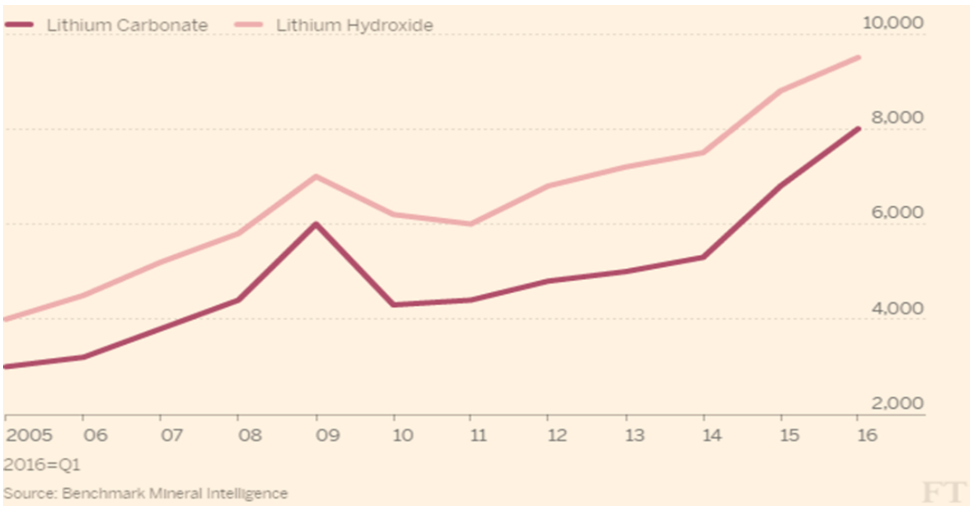

Figure 4 *Price development for lithium carbonate and lithium hydroxide, 2005-2016.*
Source: *Energy and Capital (Kohl, 2016). Primary source: Benchmark Mineral Intelligence.*

As a result of the financial crisis in 2008-2009, real demand for metal applications decreased, and thus the demand for most metals and other commodities (Christian, 2009). For this reason, the commodity prices declined. For lithium on the other hand, the situation was different. Looking back, the price has steadily increased from 2005 until 2009, when it reached a peak. From 2008 until 2009, lithium production declined more than lithium demand (U.S. Geological Survey, 2017b), resulting in a higher price. Production increased by 49 percent and consumption by 24 percent from 2009 until 2010, which corresponds to the price decline following 2009. Ever since 2011, there has been an increase in the lithium price. During 2013, the market entered a situation with excess demand. Through 2014, the price increased to a level that has previously not been observed, during the timespan. The lithium carbonate price has more than doubled from 2005 until 2016. Due to the increased demand for LIBs in EVs, the lithium carbonate price developed drastically over a short period of time. In 2015, the price increased by approximately 15 percent reaching 7 500 USD per tonne of LCE (Sanderson, 2015a). By December 2017 the price had more than doubled hitting 16 000 USD per tonne of LCE (Miller, 2018).

5.2 Cobalt - deposits, producers, production, and historical price development

The aim of this chapter is the same as that of chapter 5.1. However, this chapter is presented in a slightly different manner as cobalt production is for the most part controlled by a single country. The following chapter covers cobalt extracting countries, with special attention given to the dominant production country. We will see how other countries are responding to this market power and will present cobalt resources and reserves. The chapter concludes with a review of the historical price and production development.

Similarly to lithium, the supply curve of cobalt is dependent on the time perspective. Moreover, the marginal cost of extraction gives an idea of the short run supply curve. The cost of extraction differs between the production countries. Cobalt extraction in the Democratic Republic of Congo is less expensive per tonne than cobalt extraction in Australia. The short run supply curve is dependent on the cost of extraction and the production capacity of the existing producers. As we will see, there are projects in development which eventually will alter the supply curve. However, at what time varies depending on what stage the project has reached. The time it takes from exploration until a mine is in commercial production, is dependent on whether the extraction has been approved and the location and resources have been inspected. If these requirements are fulfilled, production can be expected within five years. However, if these criteria are not met and cobalt is the primary product, the process may take eight to ten years (Bloomberg New Energy Finance, 2017a). As of May 2017, an estimate of 46 cobalt projects were under development (Bloomberg New Energy Finance, 2017a) and it is reasonable to assume that several have achieved the requirements.

5.2.1 Cobalt extraction – mainly as a by-product

Cobalt is for the most part found in different ores in the Earth's crust and on the ocean floor. Current prices and technology do not provide incentive to extract cobalt from the latter location. Primary production of cobalt is rare, it is chiefly extracted as a by-product of nickel and copper production (British Geological Survey, 2009). "In 2016 approximately 60% of cobalt mined was a by-product of copper, 38% as a by-product of nickel, and the remaining 2% from primary cobalt mines" (Global Energy Metals Corporation, n.d.-b). Consequently, the extraction of cobalt is driven by the extraction of nickel and copper, instead of its own price (Global Energy Metals Corporation, n.d.-b). The relationship between these base metals and cobalt, contributes to the supply risk of the latter.

5.2.2 Which are countries are the biggest producers of mined cobalt?

The Democratic Republic of Congo

The Democratic Republic of Congo, henceforth referred to as DR Congo, is the world's largest producer of mined cobalt. As part of the African copper belt, the country controls approximately 50 percent of global reserves. In 2017, the DR Congo produced more than half of the world's total supply, equivalent to 64 000 tonnes of cobalt (U.S. Geological Survey, 2018). The two largest copper-cobalt producing deposits, Katanga and Mutanda, are located in the Katanga province (Wilson, 2018), where cobalt extraction from the latter mine totalled one third of the overall supply in 2016 (Drummond, 2017). The DR Congo's market share is expected to increase further. From 2023 the Congolese cobalt can account for 75 percent of total supply (Burton & Mordant, 2018).

There are several factors that could potentially affect the supply of cobalt from the DR Congo in the coming years. First is the extent to which the cobalt extraction is reliant on artisanal and small-scale mining. The term artisanal and small-scale mining (ASM) covers mining which is often done illegally, by hand, by children or a combination of all the above (Miningfacts, n.d.). The Congolese authorities claim that cobalt from ASM constitutes one fifth of cobalt export from the country. However, the percentage is thought to be underestimated (Dummett, 2017). With the increased attention on battery production, the supply chain has been put under pressure to ensure that the cobalt input is ethically mined. In March 2018, the Congolese government will be introducing a system that prevents child labour and other infractions of human rights (Pilling, 2018). The intent of the rule seems to be to uphold consumer interest for the DR Congo's cobalt.

In addition to the issues related to ASM, the country struggles with political instability and a weak infrastructure (PwC, n.d.). As the country controls much of the global production, domestic decisions have the potential to affect global supply (Olivetti et al., 2017). In mid-March 2018, the president of DR Congo approved a new mining law, which defines cobalt as a strategic mineral. The law is motivated by higher royalties from cobalt mines due to an expectancy of increased demand for the metal. Some foreign investors have indicated that the law could dampen investments in DR Congo (Reuters, 2018b).

According to Olivetti et al. (2017), cobalt from the DR Congo can be referred to as a co-product of copper because it contributes in large parts to the mines income. Nonetheless, periods of low copper prices have greatly affected cobalt extraction in the country (Palisade Research, 2016). Due to Glencore's great copper production, the company is also among the top producers of cobalt and produced 27 400 tonnes of cobalt in 2017. For the most part, production came from their facilities in DR Congo (Glencore, n.d.). The low copper prices in 2015 led Glencore to cease copper production in the Katanga mine. However, the mine resumed operations late 2017 and is expected to produce 11 000 tonnes of cobalt in 2018 and approximately three times more in 2019 (Reuters, 2017b). With the additional supply from Katanga, Glenore's production in 2018 is estimated to reach 39 000 tonnes of cobalt (Payne & Zhdannikov, 2018). While increased production from the Katanga mine can decrease the forecasted cobalt deficit, the company is only expected to increase cobalt extraction as long as the price creates incentives to do so (Sanderson, 2017c).

China consumes more cobalt than any other country. Although China controls most of the cobalt refinery production, they are reliant on imports from DR Congo as their domestic cobalt extraction is low (U.S. Geological Survey, 2018). Consequently, there are concerns that the country is in the process of monopolising large parts of the Congolese supply (Payne & Zhdannikov, 2018).

The cobalt production from the other countries cannot be compared to that of DR Congo. The market leaders' extraction is 11 times higher than that of the second largest producers' (U.S. Geological Survey, 2018). Since China is securing large parts of the cobalt production from DR Congo and the demand for cobalt is great, several projects are being developed outside the country. These projects have the potential of adding to the global supply. For example, both Australia and Canada are about to expand their cobalt industry and Korean and Japanese firms are among those who are looking to secure supplies from these growing market players (Burton & Mordant, 2018).

Australia

As seen in the lithium chapter Australia is rich in natural resources, which have also made them the third largest producer of mined cobalt. In 2017 the country produced 5 000 tonnes of cobalt as a by-product of both nickel and copper, and their estimated reserves are 1.2 million tonnes (U.S. Geological Survey, 2018). Located in Western Australia, cobalt is produced from the Murrin Murrin mine, operated by Glencore (Benchmark Minerals, 2016), and from the Ravensthorpe operation (First Quantum Minerals LTD., n.d.). Although production of cobalt in Australia is costlier compared to the DR Congo (Burton, 2017), the country has several projects in development (Benchmark Minerals, 2016). Motivated to supply the battery market with nickel and cobalt sulphate, Clean TeQ has initiated the Syerston project (Benchmark Minerals, 2016). Excluding the deposits in the African Copper belt, the Syerston project holds the greatest resources with the highest content of cobalt and nickel (Clean TeQ, 2016). This deposit is estimated to hold 114 000 tonnes of cobalt and 700 000 tonnes of nickel. (Benchmark Minerals, 2016). The Syerston project is expected to reach commercial production during 2020, supplying 3 200 tonnes of cobalt annually (Benchmark Minerals, 2016) and will be benefiting from a well-developed infrastructure (Clean TeQ, 2016). Australia has several other projects in development, among these are the Mount Gilmore and the Thackaring Cobalt Project. However, these are still in pre-feasibility stages and it will likely take several years before the projects can contribute to supply (Benchmark Minerals, 2016).

Canada

While Canada is the fourth largest producer of cobalt, the country can be ranked as the number one cobalt explorer outside of the DR Congo (Benchmark Mineral, 2016). Canada produced 4 300 tonnes of cobalt in 2017 whereas their reserves are estimated to be 250 000 tonnes of cobalt (U.S. Geological Survey, 2018). Already in 1996, the Canadian company Fortune Minerals Ltd identified the NICO deposit (Fortune Minerals Limited, n.d.). Despite great investments, the deposit is still not producing any cobalt. Should the project reach completion, it could supply the cobalt market with 2 000 tonnes per annum. However, the project need to get permission and financing to develop a working infrastructure system and the completion date depends on whether sufficient funding can be secured (Friedman, 2018). The NICO project is one of several in Canada. The Lynn lake project, owned by Corazon Mining Ltd. and several others by Cruz Capital, are among the projects in pre-feasibility stages. The Lynn lake project is promising as it has been an area for nickel and copper production for several years (Benchmark Minerals, 2016).

5.2.3 The size and location of the cobalt reserves and identified resources

USGS estimates that the current global cobalt reserves are 7.1 million tonnes of cobalt, an increase of 100 000 tonnes from the previous year. Both the DR Congo's and Australia's estimated reserves increased from 2016 to 2017, indicating that the latest price increase of cobalt has incentivized exploration or made poorer deposits economically extractable. However, the estimated reserves of New Caledonia dropped from 64 000 tonnes to zero from 2016 to 2017, due to declining nickel prices. Likewise, nickel prices seem to have affected Canada's reserves as both their cobalt and nickel reserves declined. Land based global identified resources are reported to be 25 million tonnes of cobalt, whereas an estimate of 120 million tonnes of cobalt resources is found on the seabed. (U.S. Geological Survey, 2017c; U.S. Geological Survey, 2018).

5.2.4 Historical price and production development for cobalt, 2010-2017

Since cobalt production depends on the production of copper and nickel, the development of the price and production of cobalt is best explained in the context of changes in the market for these base metals. The cobalt contract, CO, traded on the LME, is for refined cobalt (LME, n.d.). Since pure cobalt is not used in LIBs, there is a distinction between the spot price provided by the LME and the price of the chemical compound used in the batteries. However, "The prices are intrinsically linked, because if one was far cheaper than the other the industry would just buy that" (Barrera, 2018). Therefore, the prices will be assumed equal in this thesis. In addition to the possible contract for lithium, the LME is assessing a contract on cobalt sulphate as demand is expected to increase (Desai, 2017).

Figure 5 illustrates how the price of cobalt, nickel, and copper has developed from 2010. All prices are indexed, 2010=100. Beginning in 2010, it seems the prices of all three metals was starting to recover after the financial crisis. In 2011 the price of copper and nickel reached its peak levels in the sample period. However, the cobalt price did not follow the same drastic pattern. Between 2011 and 2012, turmoil in Africa reached an all time high level since 1945 (Mills, 2013), which can explain the decline in the cobalt production, illustrated in figure 6. Despite low cobalt production, the overall price in the period 2011-2012 seems to have developed with a downwards-sloping trend. Indicating that the demand for cobalt must have been low in the corresponding period. From 2011 until 2014, the price of copper was above its marginal cost, which incentivized increased copper production. The production increase could also have been a response to China's great demand for copper (Norland, 2016). Correspondingly, cobalt production increased from 105 000 to 126 000 tonnes of cobalt, between 2012 and 2015. Even though the production increased, so did the price of cobalt. The rise in the cobalt price was most likely explained by increasing demand.

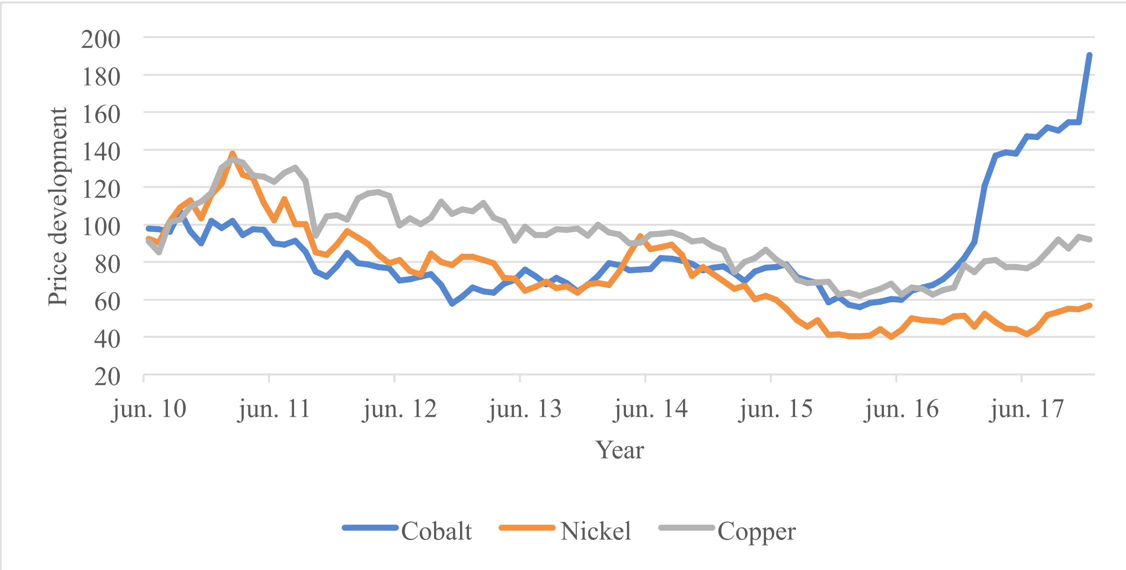

Figure 5 *Price development for cobalt, nickel and copper, 2010-2017. All have been indexed, 2010=100.*
Source*: Thomson Reuters Datastream.*

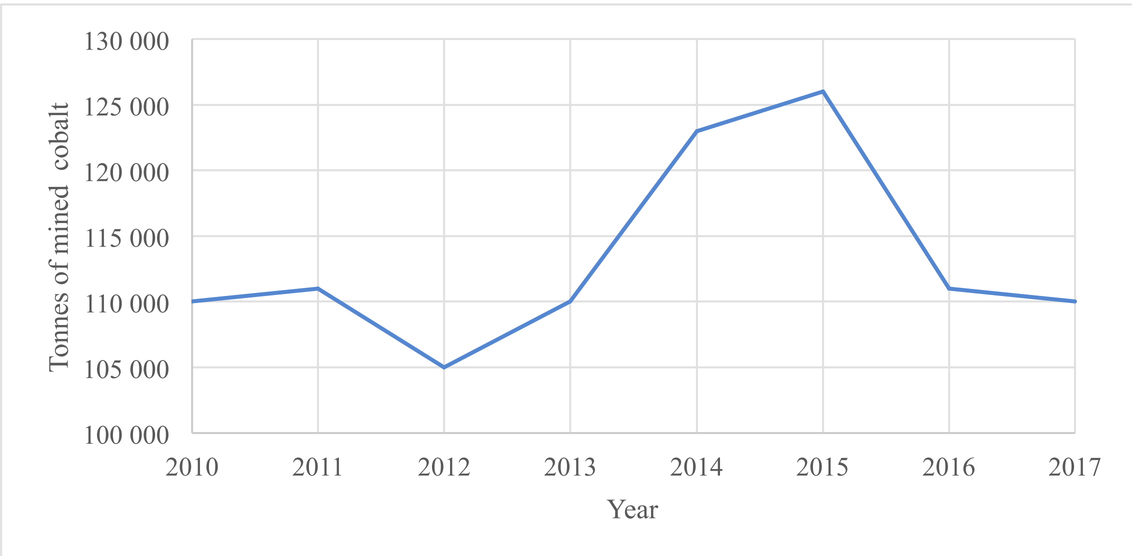

Figure 6 *Cobalt mine production in tonnes of cobalt, 2010-2017.*
Source: *Data on production is collected from USGS's 2010-2018 "Mineral Commodities Summaries".*

Several commodities were hit by a crisis in 2015, copper and nickel were no exceptions. China's demand for copper (Sanderson, 2015b) and nickel (Iosebashvili, 2015) was lower than expected, resulting in a supply surplus. Yearend 2015, many copper and nickel operations scaled down production in response to the low prices (Sanderson, 2017c) , thus the cobalt mine production declined from 126 000 to 111 000 tonnes of cobalt in 2016.

From 2015 the price development of cobalt appears to be less related to copper and nickel. Remembering figure 1, the development in the price of cobalt resembles the exponential growth of the EV stock. Following 2015, none of the industrial metals traded on the LME have had a comparable price increase to that of cobalt (Burton, 2018). The cobalt price increased by 110 percent from January until December 2017, ending at 75 205 USD per tonne of cobalt. To put this in a perspective, the price of nickel and copper respectively increased by 24 and 23 percent in the same period. Increasing demand for LIBs combined with a decreasing cobalt production can explain the exponential price increase of cobalt. By 2017 production reached its lowest level since 2013, equivalent to 110 000 tonnes of cobalt. These market conditions have lead consumers to stock up cobalt in fear of a future supply shortage (Sanderson, 2017d).

Production of cobalt is dependent on whether cobalt is defined as a by- or co-product of the two base metals. At the same time a price increase of cobalt can alter the categorization. The recent price increases are assumed to be sufficient to categorize cobalt as a co-product of both nickel and copper. As a co-product, the price ratio between cobalt and the base metals will determine the production increase of cobalt (Olivetti et al., 2016). Since predicting the copper and nickel prices are beyond the scope of this thesis, the price of copper and nickel is assumed to remain at levels where cobalt is defined as a co-product.

6 Increased electric vehicle demand: cobalt and lithium production and price forecast

In this chapter we will predict how increased demand for EVs will influence the price and production of cobalt and lithium. We approach this research question by estimating structural models on reduced form. Thus, this chapter begins with a review of this method. Followed by a presentation of the data applied to estimate the reduced form models and other data estimates that will be relevant to the discussion. Thereafter, descriptive statistics of the data sample are given. Then, the results of the reduced form models will be presented. Finally, we discuss whether the predicted relationship between the metal prices and EV sales will remain stable. The discussion is based on fundamental information on the factors we believe affect the demand and supply of cobalt and lithium, which have been presented in the previous chapters.

The market price and quantity for cobalt and lithium are, like most other goods, determined in equilibrium between supply and demand. In classic microeconomic theory the demand function is derived by maximization of utility subject to a budget constraint, alternatively, by minimization of expenditure subject to utility. The first resulting in demand as a function of real prices and income, known as Marshallian demand. The latter, Hicksian demand, a function of real prices and utility (Varian, 1992, p. 104-106). A long-run supply function is derived from the choice of problem of a profit-maximizing producer, and the supply of an output will be the function of input and output prices (Varian, 1992, p. 216).

The supply chain for both metals is intricate. Consumers do not demand lithium or cobalt, but different end applications such as EVs or mobile phones. Therefore, the production of the metals is not directly linked to demand, there are several intermediate stages. This complicates the modeling of a supply and demand function for lithium and cobalt. To do so, the demand functions of consumers, the supply function in several stages of the supply chain, the output and the input prices, and income would have to be known. The affect of EVs on the price and production of cobalt and lithium would have to be solved through a system of equations. Additionally, this method would require constant production and utility functions, which do not reflect the dynamic market conditions for cobalt and lithium.

Due to the complicated nature of modeling supply and demand functions in line with economic theory, the functions are simplified with explanatory variables believed to drive the demand and supply. In order to use OLS for estimation, the reduced form models are applied. The reduced form regressions are multiplicative, exponential functions like the following,

$$Y_t = \alpha X_t^{\beta_k} e^{u_t}$$

The dependent variable in all regressions will be either the cobalt or lithium price. The functions are estimated on logarithmic form so that the interpretation of the beta coefficients provides the point "elasticities" (Brooks, 2014, p. 85),

$$lnY_t = \ln\alpha + \beta_k \ln X_t + u_t$$

The elasticities will be assumed constant over time and applied when evaluating higher percentage changes in the independent variable on the dependent variable. Most certainly, elasticities will change over time.

When attempting to estimate the relationship between the price and quantity, one is confronted with the identification problem. I.e. it is difficult to identify whether the changes are driven by shifts in demand or in supply, or quite common shifts in both. From the reduced form model, the covariation between the dependent variable and the independent variable is obtained. In the reduced form model, the beta coefficient can neither be identified as a demand nor supply elasticity, it is rather a mongrel elasticity (Gujarati & Porter, 2010, chp. 11). Henceforth, the beta coefficient will be referred to as an elasticity. We are aware of the econometric issues, nonetheless our aim is to get an indication of how the prices are likely to develop in tandem with changes in realised demand, i.e. EV sales.

If the demand and supply functions are exactly identified, one can solve the identification problem mathematically and find the beta coefficient from the structural models. If the functions are overidentified, one should use two-stage least squares to estimate the structural models (Gujarati & Porter, 2010, chp. 11). We will not attempt to solve the identification problem mathematically or estimate the structural models by two-stage least squares, because under certain assumptions it is possible to identify what drives the price and quantity changes without having to specify a complete mathematical model. This is when we can assume that either the demand or the supply functions do not shift, as illustrated in figure 7. The curve that does not shift will be the one identified and will therefore be the curve that the reduced form model describes (Gujarati & Porter, 2010, chp. 11).

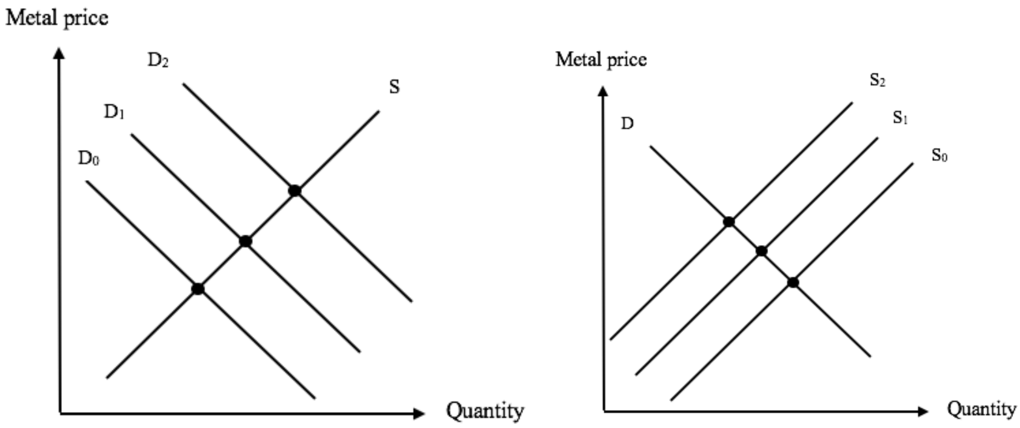

***Figure** 7 Illustration of the graphical solution to the identification problem.*

6.1 Data and descriptive statistics

The subsequent analysis is limited to a more recent period than the previous discussions. The data sample in this study covers the period from January 2014 through December 2017, on a monthly frequency. The timespan is chosen because the observations on monthly global EV sales is limited to this period. Unfortunately, this may be a short time-series sample. However, the belief is that EVs have influenced the market for cobalt and lithium in the recent years. Thus a longer time span will perhaps not be more useful in investigating the impact of a further EV adoption on these metal markets.

The following data is applied to estimate the reduced form models and table 3 shows the corresponding abbreviations for the variables. The Solactive Global Lithium Price Index is used as an estimate for the spot price of lithium. “The Solactive Global Lithium Index tracks the performance of the largest and most liquid listed companies active in exploration and/or mining of Lithium or the production of Lithium batteries” (Solactive, 2018). Henceforth, the index will be referred to as the lithium price. Furthermore, the spot price of cobalt, nickel and copper in USD per tonne is used. These are published by the London Metal Exchange (LME). The WTI spot price and the index for Industrial Production (Consumer Goods) from the Federal Reserve Economic Database will also be included. The latter will be a proxy for the end-consumers income. The data above is downloaded from Thomson Reuters Datastream. The data on monthly global EV sales are published by Inside EVs (n.d.).

To assess the price development and risk of lithium and cobalt in relation to other metals, the London Metal Exchange Index (LMEX) in USD per points is used as a proxy for the metal market behavior. The LMEX is downloaded from Thomson Reuters Datastream.

Table 3 *Abbreviations used in chapter 6.*

Variable	Abbreviation	Variable	Abbreviation
Electric vehicle sales	EV sales	Nickel price	NiPrice
Lithium price	LiPrice	Copper price	CuPrice
Cobalt price	CoPrice	WTI	WTI
London Metal Exchange Index	LMEX	Industrial Production (Consumer Goods)	ConsIndex

Moreover, the following estimates are needed for the discussion. As a starting point to predict the future price development, the spot price of cobalt and the global average lithium carbonate price in December 2017 is used. The latter is published by Benchmark Mineral Intelligence in their "Lithium December 2017 review" and downloaded from Thomson Reuters Eikon (Miller, 2018).

The low and high demand scenario's CAGR in EV sales as explained in chapter 3.5 are applied in combination with the beta coefficients for EV sales to obtain the predicted price growth of cobalt and lithium. In addition, the CAGRs are used to estimate future annual EV sales based on an estimate of the EV stock in 2017[4,5]. These EV sales in combination with the amount of cobalt and lithium in one EV[6], are used to find the amount of cobalt and lithium needed for the annual EV sales.

In addition, estimates of the cobalt and lithium production in 2017 and the current production capacity are used in the discussion. The global lithium content production in 2017 and the

[4] The estimated EV stock in 2016 by the International Energy Agencies and EV sales in 2017 from Inside EVs is used as a proxy for the global EV stock in 2017 (International Energy Agency, 2017; Inside EVs, n.d.).

[5] $EVstock_{2017} * (1+CAGR)^t – EVstock_{2017} = \text{Annual EV sales}_t$

[6] See chapter 4.3 for estimations and sources.

global yearly lithium production capacity in 2016 are estimated by the U.S. Geological Survey and collected from the report “Mineral Commodity Summaries 2018”. The lithium content has been converted to lithium carbonate equivalent (LCE) by using conversions provided by European Metals Holdings Limited (2015). The global cobalt mine production in 2017 is collected from the U.S. Geological Survey’s report “Mineral Commodity Summaries 2018” as well. The worldwide annual cobalt refinery production capacity in 2015, is taken from the U.S. Geological Survey’s report “2015 Minerals Yearbook, Cobalt Advance Release” and will be used as a proxy for the worldwide annual cobalt mine production capacity.

The minimum years it takes from exploration of a lithium brine until it can come into commercial production is used as a proxy for how many years it takes to increase production capacity. That is approximately five years. Likewise, the construction of a cobalt mine is assumed to take five years[7]. Thus, the short time horizon covers the timespan from 2018 through 2022. The lithium and cobalt production capacity is assumed to keep constant within the short run.

The remainder of this section will cover the price development of cobalt and lithium during the sample period and descriptive statistics of the data used for the estimation of the reduced form models. Figure 8 shows the price development of cobalt, lithium, and the metal market in the sample period. From 2014 until the beginning of 2016, the three graphs followed each other quite closely, where it seems they shared a slight downward sloping trend. By 2016, when the price of lithium, cobalt, and the LMEX started to recover, the two metals began to deviate more from the market compared to the previous period. Explaining variations in the lithium and cobalt price due to variations in the metal market demonstrate that the prices are, for the most part, driven by unsystematic risk factors. The share of unsystematic risk for lithium and cobalt is 78 and 96 percent, respectively[8]. By the end of 2017, the market ended just above the base value of 100, whereas the two metals showed a much greater growth. Especially the cobalt price had an exceptional growth, starting below 100 in 2016 and increasing to more than 250 in 2017.

[7] See chapter 5.1.1 and 5.2 for sources.
[8] The share of unsystematic risk is found by regressing the metal prices on the LMEX.

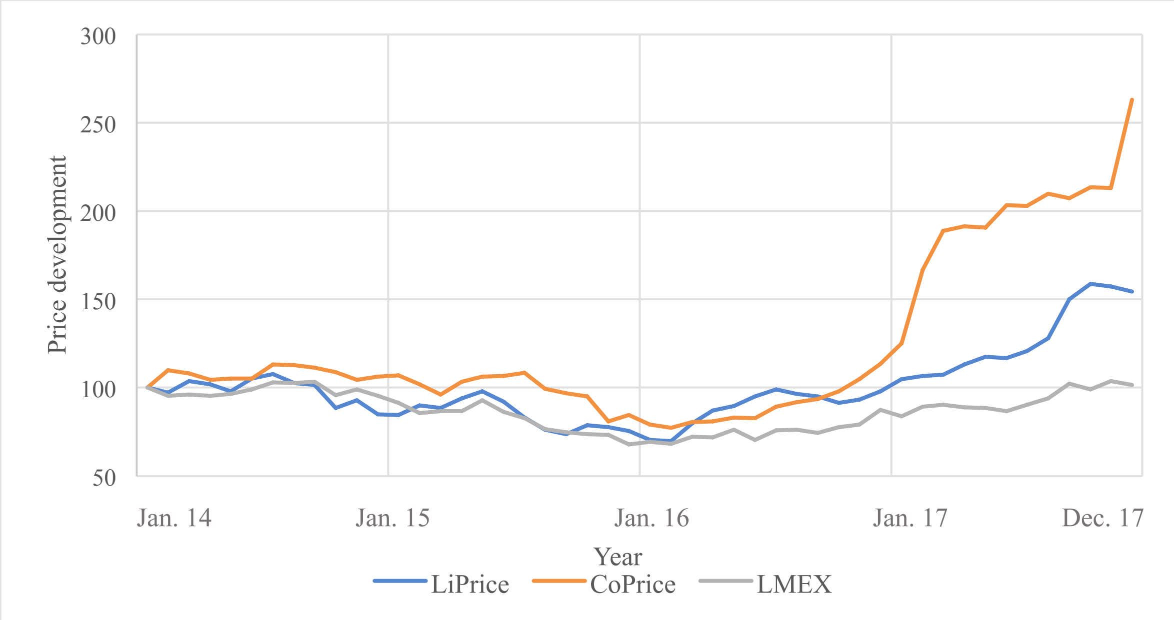

Figure 8 *Price development for lithium, cobalt, and LMEX, 2014-2017.*
All have been indexed, January 2014=100.

The descriptive statistics for the data sample is given in table 4, here the mean and standard deviation are estimated from logarithmic percentage changes of the data. Both the lithium and cobalt price have had a higher average yearly return than the LMEX and are more volatile. The result is as expected, due to the price development of the two metals during 2016-2017, when they increased rapidly compared to the market. The mean yearly return of the cobalt price is more than twice as high as that of the lithium price and the volatility is greater. A potential explanation for the differences in volatility may be that the lithium price is proxied by an index of companies and variation can be reduced by diversification. The high average yearly percentage change in EV sales could be explained by the increased number of sales during 2016 and 2017. The negative average yearly return for both the copper and nickel prices is not surprising after observing the price development of these metals in chapter 5.2.4.

Table 4 *Descriptive statistics of the sample data, annualized, 2014-2017.*

	Mean	**St. Dev**
LiPrice	11.1 %	20.5 %
CoPrice	24.7 %	24.6 %
LMEX	0.4 %	15.8 %
EVSales	63.8 %	97.0 %
NiPrice	-4.9 %	27.2 %
CuPrice	-1.3 %	20.3 %
ConsIndex	1.6 %	2.5 %
WTI	-12.6 %	35.6 %

Note: The data are logarithmic percentage changes. N=47 monthly observations.

The correlation matrix for the data used in the reduced form models is shown in table 5. The most interesting linear relationship to notice is between the price of both cobalt and lithium and EV sales. The cobalt price and EV sales have a higher correlation than the price of lithium and EV sales. The relationships between both NiPrice and CuPrice and EV sales are also of particular interest. While these metals are also used in EVs, they do not exhibit the linear relationship we would have expected. Some of the correlations may be high enough to cause problems with multicollinearity in some of the reduced form models, for example, the correlation between the NiPrice and CuPrice.

Table 5 *Correlation matrix at levels, 2014-2017.*

	LiPrice	**CoPrice**	**EVSales**	**NiPrice**	**CuPrice**	**ConsIndex**	**WTI**
LiPrice	1						
CoPrice	0.88	1					
EVSales	0.70	0.75	1				
NiPrice	0.08	-0.11	-0.49	1			
CuPrice	0.55	0.42	-0.05	0.76	1		
ConsIndex	0.31	0.44	0.75	-0.75	-0.49	1	
WTI	0.12	-0.07	-0.46	0.89	0.77	-0.81	1

Note: N=48 monthly observations.

The data has been tested to see whether the series are stationary or not using the augmented Dickey-Fuller test. All variables are non-stationary, besides EV sales which was found to be a stationary process. It is therefore a possibility that our regressions are spurious. Meaning that there may not be a causal relationship between the dependent and the independent variables we find to be significant. (Wooldridge, 2014, p. 507-512).

6.2 Empirical results from the reduced form models

In this section results from the reduced form models will be presented. First, we model both the lithium and cobalt price as functions of EV sales to evaluate whether there is a causal relationship. Secondly, the aim is to give an impression of the cobalt and lithium prices at the end of 2018. Furthermore, the results from the expanded models are presented. These expanded models are the basis to determine how increased demand for EVs will influence the price and production of cobalt and lithium.

While the main focus of this thesis is not to answer the research question within an econometric framework, we have tried to the extent possible to correct for the econometric issues. The remaining problems we will disregard. With our approach multicollinearity will be an issue. If variables are highly correlated altering the specification may affect the significance and the size of the remaining beta coefficients (Brooks, 2014, p. 218). Since heteroscedasticity and/or autocorrelation were present in all regressions an attempt was made to reduce the bias of the standard error by using Newey-West standard errors. While this approach will not alter the size or sign of the beta coefficient, the beta coefficient can be found insignificant because the Newey-West standard errors are greater. Nor do these standard errors affect R^2. The choice of lag length correcting for autocorrelation and heteroscedasticity was chosen by inspecting correlograms (Wooldridge, 2014, p. 349-352). In the regressions with lithium and cobalt as the dependent variable we chose 3 and 4 lags, respectively.

The reduced form models used to estimate the effect of EV sales on the metal prices are as follow,

$$(1)\ lnLiPrice_t = ln\alpha + \beta lnEVsales_t + u_t$$

$$(2)\ lnCoPrice_t = ln\alpha + \beta lnEVsales_t + u_t$$

As expected, the beta coefficient for EV sales is positive for both the price of cobalt and lithium, see table 6. While it is tempting to interpret the beta coefficients as belonging to the supply curve, it is important to remember that these are mongrel elasticities. With regards to the lithium price, the estimated mongrel elasticity of EV sales is 0.16 percent, and the mongrel elasticity of EV sales on the cobalt price is 0.32. Meaning that a one percent increase in EV sales will increase the price of lithium with 0.16 percent while the cobalt price increases with 0.32 percent, ceteris paribus. Although both of them can be categorized as close to inelastic, i.e. the prices are not very sensitive to marginal changes in EV sales, the price of cobalt is affected to a greater extent than the lithium price. The coefficient of determination for the cobalt price is higher than for the price of lithium, meaning that changes in EV sales explain more of the variation in the cobalt price, than in the price of lithium.

Table 6 *Results from regression 1 and 2.*

	lnLiPrice		**lnCoPrice**	
	Coefficient	**SE**	**Coefficient**	**SE**
lnα	2.72***	0.90	6.96***	1.34
β	0.16*	0.08	0.32**	0.13
R^2	0.22		0.30	

Note: *, ** and*** indicates that the regression coefficients are significantly different from zero at a 10 %, 5 %, and 1 % level, respectively.

The beta coefficient for EV sales elasticity and the high demand scenario's EV sales growth rate, result in a lithium price of 16 640 USD per tonne LCE, end 2018, all else constant. The similar example for cobalt leads to a price of 81 221 USD per tonne. The observed price growths in 2017 would indicate metal scarcity to a greater degree than our models do. Table 7 shows the estimated growth in EV sales and the annual predicted growth in the cobalt and lithium price, both in the low and the high demand scenario.

Table 7 *Growth in electric vehicle sales in both the low and high demand scenario with the corresponding price growth in both the price of lithium and cobalt as a result of applying the beta coefficients from regression 1 & 2.*

	Low demand scenario	**High demand scenario**
Annual growth rate electric vehicle sales	19 %	25 %
Annual growth in lithium price	3 %	4 %
Annual growth in cobalt price	6 %	8 %

As we do not believe that EV sales is the sole factor explaining variation in the lithium and cobalt price, we have chosen to expand the models. If one does not consider the effect of econometric issues, like multicollinearity, including relevant variables could provide a more precise estimate of the beta coefficient for EV sales elasticity. To the extent possible, the attempt has been to include explanatory variables that are not highly correlated with each other. A brief explanation of these variables will be provided, before we proceed to discuss the growth in both the lithium and cobalt price solely based on the beta coefficient for EV sales elasticity.

The expanded reduced form models used to estimate the effect of EV sales on the metal prices are as follow,

(3) $lnLiPrice_t = ln\alpha + \beta_1 lnEVsales_t + \beta_2 lnConsIndex_t + \beta_3 lnWTI_t + u_t$

(4) $lnCoPrice_t = ln\alpha + \beta_1 lnEVsales_t + \beta_2 lnConsIndex_t + \beta_3 lnNiPrice_t + \beta_4 lnCuPrice_t + u_t$

The included variables can have an affect on both the demand and supply of cobalt and lithium. However, they are included with the following interpretation in mind. Income is included in regression 3 and 4 because the demand for other cobalt and lithium containing applications are driven by the income of the end-consumers. The WTI is included in regression 3 since most metal extraction processes are energy intensive and changes in the oil price can affect the operation cost and therefore supply[9]. Since cobalt is obtained from copper and nickel ores, the prices of these are included as explanatory variables for the cobalt price. The results of the regressions are given in table 8. Since the beta coefficient for income, the WTI, and the copper and nickel prices are mongrel elasticities, the interpretation of these elasticities will not be discussed.

Table 8 *Results from regression 3 and 4.*

	lnLiPrice		**lnCoPrice**	
	Coefficient	**SE**	**Coefficient**	**SE**
lnα	-22.51*	11.38	-32.47**	12.95
β_1	0.25***	0.05	0.22***	0.068
β_2	4.76*	2.49	5.55**	2.74
β_3	0.56***	0.08	-0.54***	0.18
β_4			2.29***	0.25
R^2	0.65		0.81	

Note: **, **,*** indicates that the regression coefficients are significantly different from zero at a 10 %, 5 %, and 1 % level, respectively.*

[9] CME did a similar study, explaining the variation in the copper price. They found WTI to be a significant driver of the copper price (Norland, 2016). Regression 4 including WTI gave an insignificant beta coefficient, therefore the WTI was excluded before running the regression again.

The beta coefficient for EV sales elasticity has increased with the addition of explanatory variables in regression 3, meaning that the effect of increased EV sales will result in a higher lithium price than first predicted. For cobalt, on the other hand, the beta coefficient for EV sales elasticity declined after the inclusion of other dependent variables in regression 4. Both the cobalt and lithium prices can still be classified as inelastic to changes in EV sales. According to regression 3 and 4, the cobalt price is less sensitive to changes in EV sales than the lithium price, which is opposite to the result from regression 1 and 2.

The annual price growth for lithium and cobalt in the low and high demand scenario are given in table 9. In the high demand scenario, the price of lithium and cobalt will increase annually by 6.3 and 5.5 percent, respectively, for all the years to come. A constant growth in the prices over time is in line with the Hotelling's rule, stating that under optimal extraction, the price of a non-renewable resource will increase with the discount rate (Hotelling, 1931). Compared to the Hotelling's rule, the predicted price growths do not seem unreasonable. On the basis that the prices used are nominal and both the discount rates and inflation targets in several of the countries where the extraction is located is approximately 3 percent (Central Bank News, n.d.; Central Intelligence Agency, n.d.).

Table 9 *Growth in electric vehicle sales in both the low and high demand scenario with the corresponding price growth in both the price of lithium and cobalt as a result of applying the beta coefficients from regression 3 & 4.*

	Low demand scenario	**High demand scenario**
Annual growth rate electric vehicle sales	19 %	25 %
Annual growth in lithium price	4.8 %	6.3 %
Annual growth in cobalt price	4.2 %	5.5 %

6.3 Discussion - Future price and production development of cobalt and lithium

The results of the reduced for models indicate that the price of cobalt and lithium will increase annually by 5.5 and 6.3 percent (high demand scenario), respectively. However, as seen in the previous chapters there are several dynamics in these markets that will affect the stability of the relationship between EVs and both metal prices. That is, factors that will affect short and long run price development. Remember that the short run covers the timespan before production capacity can increase, 2018 through 2022.

The mongrel elasticities for EV sales is derived from realised demand (EV sales) and the cobalt and lithium prices. The elasticities are results of shifts in demand in the metal markets where there seem to be increasing marginal extraction costs in the short run. This is illustrated in figure 9. Cobalt extraction in Australia is more expensive than extraction in the DR Congo, and the extraction of lithium from spodumene is more expensive than that of brine. In the short run, the closer production is to full capacity, the costlier it is to produce yet another tonne of cobalt or lithium. For this reason, the slope of the supply curves is growing at an increasing rate. However, at full capacity the supply curves are vertical.

Due to increased environmental concern and public policies, the demand for EVs has increased and so the demand curve of cobalt and lithium has shifted outwards. At the same time, the supply curves of these metals have remained constant and inelastic. Therefore, the price and quantity relations, regression 3 and 4, identify the supply functions of lithium and cobalt. I.e. the identification problem is solved. Thus, the elasticities can be applied when analysing further positive shifts in lithium and cobalt demand, due to increased EV sales. In figure 9, increased demand for these metals due to increased EV sales will result in a higher price and production of cobalt and lithium. The shift from D_0 to D_1 can illustrate both the low and high demand scenario. The price increase from P_0 to P_1 corresponds to the predicted price growths given in table 9. This is under the assumption that the predicted EV sales elasticities are constant over time and that the EV sales increase as predicted.

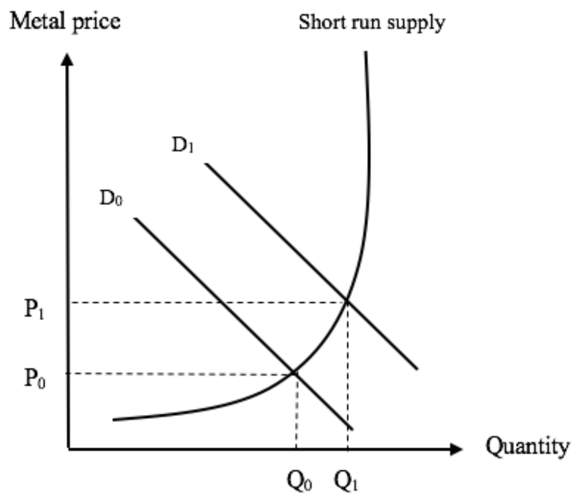

Figure 9 *Change in short run equilibrium price and production due to increased demand for electric vehicles.* ***Note:*** *metal price is the price of cobalt or lithium. Quantity is tonnes of cobalt or lithium.*

In figure 9, as demand for EVs increase, the movement along the supply curve that leads to increased production of cobalt and lithium, from Q_0 to Q_1 is assumed possible. However, the production increase requires free capacity, or else the increased demand would result in a higher price than our predicted price growths would give. The total demand (total need) for the metals will be compared to the current production capacity to examine whether the production increase is feasible in the short run. The total need for each metal is the amount consumed by EVs and other applications. As a proxy for the amount of cobalt and lithium that is consumed by other applications, cobalt and lithium production in 2017 was subtracted by the amount of cobalt and lithium needed for the EV sales in 2017. The estimated annual total demand for both cobalt and lithium is found by keeping the need for other applications constant and adding the demand from the annual projected EV sales.

According to our calculations, the total demand for both cobalt and lithium is within the current production capacity until 2024 and 2027 in the high and low demand scenario, respectively [10]. Thus, the movement along the supply curve from Q_0 to Q_1 as shown in figure 9 is possible, and the predicted price growths could occur during the short time horizon. Furthermore, the number of years until the need for the metals surpasses current production

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[10] In most cases current reserves will cover the need for the metals if the demand for other applications stays constant and the electric vehicle fleet increases as assumed until 2040. The need will only exceed reserves in the high demand scenario for cobalt. However, we do not believe that limited reserves will be a significant driver of the price of cobalt, as increased demand for the metal will incentivize exploration and technological advancements of extraction.

capacity is sufficient for new operations to be developed. This is under the assumption that the amount of cobalt and lithium needed in one EV is consumed and produced the same year the vehicle is sold. Additionally, that the manufacturers of the other applications for the metals purchase cobalt and lithium the same year it is produced.

As seen above, the producers of cobalt and lithium have the available capacity to meet the increased demand, both in the low and high demand scenario, during the short run. However, the production increases might not be probable. Even with available capacity, increased lithium demand has not always led to increased production. However, factors such as poor weather conditions and production quotas might have hindered increased output. Remember the production and price development in the lithium market 2014-2015, figure 3 and 4. The major lithium companies in Chile have recently received increased extraction quotas and the available capacity is presumably spread throughout several countries. Thus, we find it unlikely that constraints such as weather and quotas will hinder a movement along the supply curve. Meaning that the increased production from Q_0 to Q_1 as seen in figure 9, seem probable. Therefore, the predicted lithium price growths from table 9 seem likely. For cobalt on the other hand, most of the available cobalt extraction capacity is likely to be located in the DR Congo. This makes it is difficult to predict if the increased demand for EVs will result in increased cobalt extraction. The formerly closed Katanga mine accounts for at least half of the available cobalt capacity[11]. If Glencore's production in the Katanga mine resumes, cobalt extraction would be closer to full capacity. Glencore has been operating in the DR Congo for at least a decade and has obtained major stakes in the largest mines, making them familiar with the conditions in the country. Thus, when Glencore announces production increases we consider them credible and feasible. In the short run, we find it unlikely that the party that holds the remaining available capacity in the DR Congo will be able to increase production while the government is attempting to reduce artisanal and small-scale mining[12]. The cobalt need in the low and high demand scenario can be covered by Glencore's additional production from the Katanga mine[13]. However, in the high demand scenario the need for cobalt will just barely be met. Nevertheless, the shift along the supply curve that leads to

[11] Total production capacity minus cobalt production in 2017 equals the estimate of available capacity (22 000 tonnes of cobalt). Glencore's projected production in the Katanga mine is 11 000 tonnes.

[12] As a consequence of increased awareness of the ethical issues related to ASM, in 2016 cobalt extraction from these mines declined by 35 percent (Bloomberg New Energy Finance, 2017a).

[13] Resumed production at the Katanga mine is found by Rawls to be a factor that can alleviate the demand deficit until 2020 (Bloomberg New Energy Finance, 2017a).

increased production of cobalt from Q_0 to Q_1, as seen in figure 9 seems probable and thus the predicted price growths could occur.

Rising lithium and cobalt prices would incentivize increased production capacity[14]. Both new and existing market players will implement exploration and mine projects. Additionally, technological developments can enable an increased extraction rate or make it possible to obtain more of the metals from the same amount of raw material. Furthermore, previously uneconomical deposits can be utilized due to higher prices. These actions will most likely be implemented during the short time horizon. As seen in chapter 5 several of these measures have already been put into action. However, it takes time to develop projects and there are most certainly barriers such as regulations and start-up costs. Thus, the impact of these actions on supply will occur with a time lag, i.e. affect the supply in the long run. The actions taken to increase production capacity would result in a more elastic supply curve and even a shift. The long and short run supply curves are illustrated in figure 10. Most likely, the first cobalt projects to come into completion will be copper-nickel deposits because primary cobalt mines have a longer construction period. When pure-play cobalt mines eventually emerge, the cobalt production will react more to fluctuations in its own market[15].

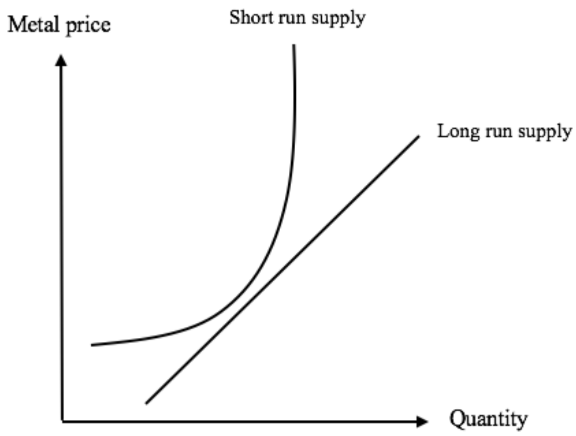

Figure 10 *Illustration of the short and long run supply curves for cobalt and lithium.*
Note: *The metal price is either the price of cobalt or lithium. Quantity is tonnes of cobalt or lithium.*

[14] We define technological development and mine projects as measures to increase production capacity.
[15] Olivetti et al. (2017) find that technological improvement will enable several primary cobalt mines, making the metal more adaptive to changes in its own market.

There are some factors that can hinder increased lithium supply in the long run[16]. Firstly, indigenous people inhabit the locations were capacity increases are likely to occur. Secondly, there is extensive damage inflicted on the environment during lithium extraction. We assume that these factors will not hinder capacity increases as the mistreated party could be compensated. Alternatively, the lithium mines could be established somewhere were the problems are minimized, as the reserves are found throughout the world. Finally, while great start-up cost could pose an issue for new projects, several are already in development so lacking capital does not seem to hinder increased capacity in the lithium market. For cobalt on the other hand, extraction can no longer be dependent on artisanal and small-scale mining to the extent it has been. These mines will not be able to increase production capacity on the scale that will be required if the EV production increases as predicted. There are large fixed costs associated with capacity increases. Thus, the major companies must implement the capacity expansions. These companies will carry out the investment if the future cobalt prices are thought to make them profitable. Glencore's market value and the fact that several projects are in development indicate that the investments in increased capacity will be implemented. For this reason, we find that there will be sufficient investments to increase cobalt production capacity in the long run.

The elasticities from regression 3 and 4 are derived from realised demand and the metal prices in markets as was illustrated in figure 9. The actions to increase production capacity alter the slope and shifts the supply curves in the long run. Therefore, the predicted price growths derived from the elasticities can no longer apply when analysing the affect of increased demand for EVs in the longer timespan. In the long run, changes in the supply curve can, to some extent, counteract the effect of increased demand for EVs on the metal prices.

The discussion regarding the short run responses of the extraction companies, comes with the requirement that battery and EV manufacturers[17] purchase the metal they need the same year the EV is sold. Most likely, this is not the case. Such a strategy would put the manufacturers at risk of running out of inputs for their battery production. Which means that the EV

[16] Öko-Institut (2017) highlights how negative externalities of extraction on the environment and society, can be constraints on short term production increases of cobalt and lithium while also proposing measures that can reduce these problems in the long run.

[17] We include both battery and EV manufacturers since some EV manufacturers produce their own batteries.

manufacturers might not be able to produce EVs as planned. Consequently, the battery and EV manufacturers are likely to stock up on the metals, i.e. purchase greater amounts of cobalt and lithium than needed for the EVs sold that year. This seems to be the current situation in the cobalt and lithium market[18]. The battery and EV manufacturers will purchase lithium and cobalt in excess of need, regardless of which EV growth rate is assumed. Thus, the shift in demand will be greater than if the manufacturers had purchased the metals according to our calculations of need. We find that the prices will increase due to expectations of insufficient supply during the short time horizon. Meaning that, increased demand for EVs will drive up the prices of both cobalt and lithium. For both cobalt and lithium, the equilibrium price and production are found at the vertical part of the supply curve, resulting in a higher price, P_2, than our model predicts. The situation is illustrated in figure 11.

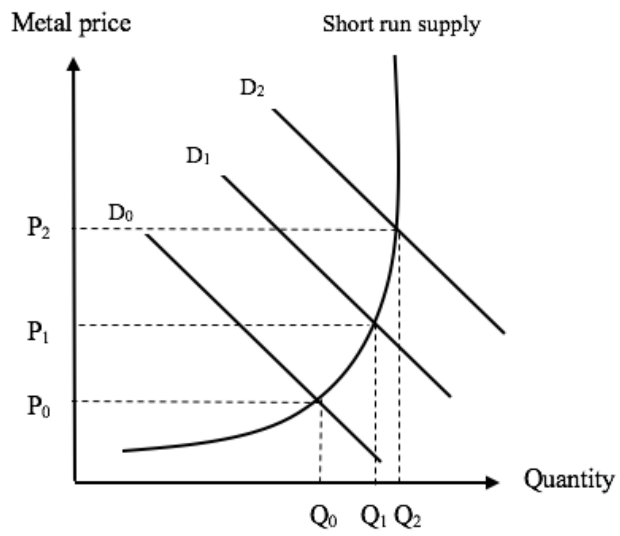

Figure 11 *Change in short run equilibrium price and production, due to expectations of insufficient supply causing a greater demand shift from D_0 to D_2.* ***Note:*** *metal price is either price of cobalt or lithium. Quantity is tonnes of cobalt or lithium.*

The expectations of the battery and EV manufacturers will change the closer the projects are to completion. Towards the end of the short time horizon the battery and EV manufacturers will be less inclined to store the metals. It is reasonable to assume that the battery and EV manufacturers will believe that their cobalt and lithium demand can be covered by the coming increased supply. Therefore, the price growths of cobalt and lithium will gradually decline towards the end of the short time horizon. Considering that some lithium projects can be

[18] The argument is consistent with Rawls' view, that consumers and producers will store any excess production of cobalt at least until 2021 (Bloomberg New Energy Finance, 2017a).

completed in 2018/2019, and new extraction technologies will be in use by 2021, the supply curve can to some extent be altered during the short time horizon. The cobalt project in Australia with completion date in 2020, has an estimated production we find unlikely to have the same influence on the supply curve of cobalt. Thus, the consumers' expectations regarding lithium availability may change at an earlier time than the expectations of cobalt. Consequently, the lithium price growth is likely to decrease prior to the price growth of cobalt. Not without saying, there are projects we have been unable to map out. These could certainly affect both the cobalt and lithium supply curve during the short time horizon.

The number of EV sales we have applied in the short term seems reasonable given that the EVs are not price competitive. From 2018 until 2022, the annual number of EV sales is approximately equal to the number of EVs sold in 2017, in both the low and high demand scenario. Nevertheless, we find the EV sales to be sufficient to drive up the price of cobalt and lithium in the short term. Extraction of cobalt and lithium is close to the capacity limit. Moreover, the battery and EV manufacturers are worried about running out of input factors for the EVs that will actually be produce. An EV revolution requires that the EV can compete on price with the ICE. As seen in chapter 4, the price of the EV battery prevents this competitiveness. The rising prices of cobalt and lithium in the short term will make the battery more expensive under the assumption that no other cost reductions occur. This will continue to prevent price competitiveness. Meaning that the EV will not be the preferred choice for the vast majority, i.e. there will be no EV revolution following 2022.

However, we have seen that both countries and vehicle manufacturers have goals for the EV production. For this reason, several vehicle manufacturers have most certainly carried out EV investments. Moreover, there is a race between the vehicle manufacturers to reach price competitiveness. Consequently, vehicle manufacturers will not remain passive in response to the increasing prices of their input factors. The battery and EV manufacturers will attempt to reduce the battery price. Price competitiveness could be reached without reducing the amount of cobalt and lithium in the batteries. Total battery prices could be reduced by economics of scale or technological improvements. This will result in a situation with immense demand for EVs and an equally high demand for cobalt and lithium. In such a situation the price of cobalt and lithium can reach a level where the battery price is driven by the price of cobalt and lithium. Once again, the battery will prevent price competitiveness between the EV and the ICE. In order for the EV to become price competitive, the manufacturers will have to find ways to make them less dependent on cobalt and lithium. In addition, they will have to reduce the overall battery cost by economics of scale and technological advancement. The means by which the cobalt and lithium amount can be reduced include perfect or partial substitution of cobalt and lithium. Alternatively, the introduction of a completely new battery technology free from cobalt and lithium.

It is reasonable to believe that battery and EV manufacturers expect increased supply of cobalt and lithium since extraction companies will adapt to the price level. Even though supply is expected to increase the demand for the metals will also increase and so the outcome on price is uncertain. Hence, battery and EV manufacturers will attempt to reduce the proportion of cobalt and lithium in the battery despite the expectance of increased supply. Altering or developing a completely new battery technology will take time. However, escalating prices of cobalt and lithium will most likely increase the rate at which the battery technology in EVs is altered. We have no prerequisites to know when the changes will occur but battery advancements can at least be expected during the long run. When the battery technology is modified, increased demand for EVs will have less of an affect on the demand for cobalt and lithium.

We found that primary supply would increase in response to increased demand for EVs. The recycling industry will in the same way react to the rising prices. Further research on recycling of the metals in the batteries will be incentivized. Moreover, increased cobalt and lithium prices are likely to expedite a functioning recycling system. When the system is developed, secondary supply of cobalt and lithium will shift the supply curve outwards. However, the system may take some time to develop and the available LIBs to recycle are few. As such, recycling will not contribute much to short run supply. The same conclusion is drawn by Olivetti et al. (2017) and Vikström et al. (2013). Besides the increasing prices, recycling is motivated by environmental concerns. Meaning that even if the prices where to decline, recycling will continue to improve and provide additional supply.

If the cobalt and lithium prices increase substantially, a situation may occur where EVs are no longer of importance and the focus turns to developing the hydrogen vehicle. However, the latter is currently not an attractive priority due to the lack of fueling stations. Investments in fueling stations are likely to be funded by the governments, but not as an immediate response to the increasing prices of cobalt and lithium. We believe that the actions taken by the other actors as discussed above, will be implemented prior to any investment decisions being taken. The governments will observe the responses from the other actors and a decline in the price of both cobalt and lithium will be expected. Thus, we find it unlikely that investments will be put towards the fueling stations, and the vast majority will not adopt hydrogen vehicles.

From the discussion above we draw the conclusion that the price of both cobalt and lithium will increase in the short run. We base this on the metal consumers' expectations of cobalt and lithium scarcity and a metal supply that cannot increase beyond the current capacity in the short run. However, towards the end of the short time horizon as projects come into completion, expectations will change and thus the price growths of both cobalt and lithium will decline. Since the difference in the annual EV sales in the low and high demand scenario is minor until 2022, the outcome on the short-term metal prices will not be dependent on which EV growth rates that take place.

The price and production development in the long run is more uncertain, as both supply and demand are likely to change. The long run equilibrium price and production of cobalt and lithium will depend on the magnitude of the demand and supply shifts in relation to each other. When the EV becomes price competitive we cannot know which EV growth rate that will occur. Meaning that it is uncertain whether the demand for EVs will be close to the low or the high demand scenario. The high demand scenario naturally leads to a greater shift in demand for cobalt and lithium compared to the low demand scenario. However, in the long run we do not believe that the price outcome will be completely dependent on which growth rate in EVs sales that was to occur. If the demand resembles the high demand scenario, secondary supply will play a more significant role in meeting the demand. Moreover, the development in the battery technology will most likely reduce the amount of cobalt and lithium[19] in the LIB. Thus, the demand shift in neither the low nor high demand scenario will be as great as anticipated. In the long run, increased production capacity, improved extraction technology, and secondary supply will alter and shift the supply curve outwards. For both cobalt and lithium, we predict a less positive shift in demand and increased supply in the long run. However, the ratio between the shifts cannot be known for certain. In our opinion, the shift in supply will outweigh the shift in demand. In time the markets will adapt to the

[19] This argument is in line with Narins (2017) who finds that substitution of lithium in the LIB will be a factor contributing to a decrease in the lithium price in the long run.

significant demand driver that EVs will be. Hence, following 2022, the prices of both cobalt and lithium will stabilize at a lower level than the observed prices in December 2017.

7 Tentative conclusions on future price and production

Several countries have eagerly implemented targets for the electric vehicle adoption chiefly due to climate concern. Which in turn has led to predictions of an electric vehicle revolution. The lithium-ion battery is the most widespread technology used to power the electric vehicle. Even though the lithium-ion battery technology has altered over the years, cobalt and lithium are still two essential components due to the characteristics they provide. If the electric vehicle was to be commonly adopted, the demand for cobalt and lithium is expected to escalate. In terms of the price and availability, cobalt and lithium have become two of the most debated metals. The concern is that they can delay or even prevent the electric vehicle revolution. Therefore, the intent of this study was to analyse how increased demand for electric vehicles will influence the price and production of cobalt and lithium.

As a starting point for our analysis, we mapped out three factors that in tandem with increased demand for electric vehicles will play a significant role in determining the long-run equilibrium price and production of both cobalt and lithium. Firstly, current and future battery technology was highlighted. Here we noticed how researchers are continuously attempting to improve the battery technology and reduce the amount of cobalt and lithium in the lithium-ion battery. These technological changes will be important in determining the magnitude of future lithium and cobalt demand. Secondly, the focus was on recycling possibilities of cobalt and lithium from the lithium-ion battery. Secondary supply will make the market less dependent on primary production, thus several actors are attempting to develop a functioning recycling system. Finally, present and future actions taken by metal extraction countries and companies were mapped out. The purpose was to get an impression of the short and long run supply curve. We noticed that marginal cost of extraction differed between countries and extraction methods. Furthermore, we saw that increased prices have already led to responses by both extraction companies and countries for both cobalt and lithium. Several cobalt and lithium projects have been implemented and extraction technologies are improving. For lithium, these projects are especially concentrated in South America and Australia. For cobalt on the other hand, while current cobalt production is dependent on the Democratic Republic of Congo, several projects are being implemented in other countries. These projects are an attempt to reduce the supply risk caused by dependence on the politically unstable Democratic Republic of Congo.

We approached the research question by using the information of the three factors to evaluate if the covariation between electric vehicle sales and the metal prices will remain stable. The covariation was derived from estimating the structural demand and supply functions on reduced form. In the discussion section we made a distinction between the short and long run, as the markets cannot adapt to price changes to the same extent in these time horizons. The short run covers the period from 2018 through 2022, while the long run extends from 2022 through 2040. In addition, we created a low and high demand scenario (with the forecast of an electric vehicle stock of both 176 million and 530 million in 2040), to see if the difference would make a great impact on the price and production development.

When estimating reduced form models the identification problem arises. However, we identified the regressions as belonging to the supply functions, since it has been a surge in demand for the metals due to increased demand for electric vehicles. The beta coefficient for electric vehicle sales was found to be a significant driver of both the price of cobalt and lithium. Results from the reduced form models imply that the price of cobalt and lithium (in the high demand scenario) will rise by 5.5 and 6.3 percent per annum, respectively.

In this research we found that during the short run, electric vehicles will drive the price of cobalt and lithium higher than the reduced form models suggest. There are two reasons for the rising prices during the short run. First of all, the short run supply curves are growing at an increasing rate before turning vertical when reaching full capacity. Next, battery manufacturers will purchase in excess of need due to the expectations of metal scarcity. Therefore, both cobalt and lithium supply will meet demand at the vertical end of the supply curves. The short run price outcomes apply in both the low and high demand scenario since the difference between the electric vehicle sales is negligible during the short time horizon.

In the long run, the price of cobalt and lithium will stabilize at a lower level than the observed prices in December 2017. Our findings for the long-run price development can be explained by changes in the three factors that will affect the price and production development of cobalt and lithium. As the cobalt and lithium markets have had time to adjust to the increased demand, then secondary supply, technological improvements of extraction, and several cobalt and lithium projects will alter the slope and shift the supply curve outwards. In order for an electric vehicle revolution to arise, the battery price will have to be reduced. We find that in addition to reducing the price of the battery by technological development and economics of scale, the proportion of cobalt and lithium in the battery must also be decreased. Thus, the demand for neither cobalt nor lithium will be as high as anticipated. This applies to both the low and high demand scenario. In our opinion, the positive shift in supply will compensate for the shift in demand. For this reason, the price of both cobalt and lithium will decline in the long term.

In the short run, the electric vehicle will be a considerable driver of cobalt and lithium demand. Increased demand for electric vehicles will increase the price and to some extent the production of both cobalt and lithium in the short run. Several are worried that the rising prices of cobalt and lithium will prevent an electric vehicle revolution. According to our research, the long-run price of both cobalt and lithium will decline and stabilize at a lower level than the observed prices in December 2017. The decrease is partly a result of increased production. Thus, in our opinion the availability of cobalt and lithium and therefore the prices will not be an obstacle for the electric vehicle revolution.

There are obviously some limitations to our study. We have had to make some assumptions that do not reflect a dynamic market. This is a very young technology and the market may see dramatic changes. Electric vehicle sales will most likely not evolve at a constant rate. In our calculations we assumed that the share of cobalt and lithium in the battery was constant throughout the time horizon. Furthermore, we did not take into account the price development of copper and nickel, both important metals when determining cobalt extraction. For obvious reasons, we have a very short data sample, which makes the estimated parameters uncertain. In our calculations the difference between the low and high demand scenario was limited. This complicated the distinction between the two demand scenarios, perhaps leading us to underestimate the importance of the size of the stock.

An electric vehicle revolution can result in increased demand for several other metals in the battery technology than cobalt and lithium, for example graphite, nickel, and manganese. As our topic was already broad we did not attempt to cover them all but encourage others to do so. A quantitatively based analysis of the lithium price and production development should most definitely be repeated if lithium was to become trade on an exchange. Finally, since the electric vehicle is a new demand driver for both cobalt and lithium, the area of research needs continuous re-examination.

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