Forecasting the Effects of Battery Recycling on the Global Cobalt Market

Elena Cavallero

Professor Brian Murray, PhD., Faculty Advisor

Professor Grace Kim, PhD., Seminar Advisor

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Abstract

This paper addresses existing concerns around a potential cobalt supply shortage driven by lithium-ion battery demand. Using econometric simultaneous equations, historical global cobalt supply and demand are estimated using data from 1981 to 2018. Based on the results of a Three-Stage Least Square estimation model of global supply and demand, this study forecasts global cobalt price and quantity in 2030. Additionally, a parametrization of battery recycling is added to study the effects of cobalt recovery on future market equilibrium. The results indicate that: 1) world GDP is a key determining driver of cobalt demand, 2) conflicts in the Democratic Republic of Congo, the world's largest cobalt supplier, negatively impact global production, and 3) recycling lithium-ion batteries will increase global cobalt quantity supplied by 23% and decrease price by 60% in 2030 under the EU Green Deal regulations.

JEL classification: C30, Q31, Q55
Keywords: Cobalt, Recycling, Simultaneous Equation, Forecast.

I. Introduction

Background and Intentions

As a result of a 40% year-on-year increase in electric vehicles (EVs) sales (IEA, 2020), the demand for lithium-ion batteries (LIB) has increased significantly. By 2030 the number of EVs on the road is expected to reach 230 million (IEA, 2030). As a direct consequence, the World Bank estimated that LIB demand will increase by 1000% (World Bank, 2017). However, the scarce availability of cobalt, a metal often used in conventional battery chemistries for its energy density and range, is a potential limiting factor in the deployment of LIBs. According to the International Energy Agency's *Stated Policy Scenario*, battery demand for cobalt is estimated to increase almost tenfold, going from 19,000 metric tons in 2019 to 180,000 tons in 2030. Given a presumed inelasticity of cobalt supply and an expected boost in EV sales, it seems likely that cobalt reserves will be hard-pressed to meet the projected demand without a significant increase in the market price. Substitution for cobalt in LIB, although possible, has not taken place. In fact, the majority of automakers have continued to opt for more cobalt-intensive chemistries for performance gains. The collection and recycling of batteries offers a significant opportunity to ease tension between cobalt supply and demand. In the EV batteries sector, the recycling potential is significant, as vehicles' exhausted batteries will be easier to collect. In both the European Union (EU) and United States (U.S.), the current recycling rate is below 5% and barely tracked (Jacoby, 2019), as there are not any specific battery collection policies in place. However, beginning in 2025, the EU will introduce stricter regulations on battery lifecycle management as part of the EU Green Deal and the New Circular Economy Action Plan. The U.S. is still behind on battery recycling regulations, though there is optimism around the Biden

Administration's trillion-dollar bet on clean energy (Friedman, 2020). As EV sales ramp up, restrictions on the collection and disposal of exhausted batteries are expected to be put in place. This paper is an attempt to quantify the effects of the introduction of battery recycling policies on the long-term price of cobalt. Using a Partial Equilibrium model, a recycling-absent price equilibrium in 2030 will be compared to the 2030 equilibrium after the introduction of recycling. The year 2030 was chosen as the forecast time boundary for two main reasons. First, my model is based on available historical data from 1981 to 2018. Having just 38 years of data, it is unlikely that my forecast analysis can correctly predict the price and quantity of cobalt for more than 12 years into the future. Second, the average lifetime of a LIB is 12 years, which is the timeframe in which all batteries sold in 2018 can come back in the market in the form of recycled material. For these reasons, 2030 was chosen as the year of interest.

The forecasting exercise sets assumptions around an increase in EV sales, collection and recycling rate, batteries' lifetime, and battery chemistry. To better capture the effect that recycling will have on the cobalt market, it is critical to correctly identify cobalt supply and demand curves. For this reason, this paper estimates price elasticity for cobalt supply and demand using the Three Stages Least Square (3SLS) method. The main limitation of this model is the availability of 38 years of data that could decrease the predictive power of the regressions. However, the elasticity coefficient results are consistent with standard economic theory and comparable to previous studies such as the Congressional Budget Office's report (CBO, 1982).

This paper is organized as follows. In the introduction, I provide background information on the cobalt market, supply, demand, and recycling. The literature review outlines existing research on 2030 projections of the cobalt market as well as papers estimating cobalt price elasticities. The theory section introduces the simultaneous equations model, and the empirical methodology outlines the partial equilibrium method. In the data section, I introduce my dataset and forecast assumptions. In the results section, I introduce the findings of the 3SLS model and then use the obtained coefficient to perform market forecasts. In the conclusion, I summarize the findings, clarify the limitations of the study, and suggest areas of further research.

II. Global Cobalt Industry

Cobalt is the only metal used in batteries whose demand growth is projected to exceed supply growth in the next 30 years under the current cathode chemistry (McKinsey, 2018). The other battery critical metals, namely lithium, nickel, and manganese, have a more distributed and secured supply and are expected to keep up with the forecasted demand more readily. On the other hand, the cobalt market presents a highly concentrated supply structure, unethical practices in producing countries, and a long lead-time for implementing new mining projects. Moreover, cobalt will hardly be substitutable as its unique properties provide batteries with higher charge densities, cycling capacities, and power-to-weight ratios, as well as shorter recharge times (BMO Capital Markets, 2017). For these reasons, this paper focuses on the global cobalt market and studies the effects of the introduction of recycling technologies on cobalt price and quantity.

Cobalt Supply

Cobalt is a hard, lustrous, ferromagnetic metal. Considered rare, even though its concentration on Earth is of medium abundance, cobalt is mainly mined as a by-product of copper and nickel with only 20% coming from primary production (USGS, 2017). Terrestrial cobalt deposits account for all current production, but they are only a small fraction of the total available resources. As reported by the U.S. Geological Survey (USGS), the largest known concentrations of cobalt are in seafloor nodules and crusts. Of 150 million tons of known global resources, seafloor resources account for 125 million tons. In 2016, the estimated global cobalt reserves at about 7 million metric tons, of which 47% is found in the DRC. 70% of the world mine production comes from the Democratic Republic of Congo (DRC) as shown in *Figure 1* (USGS, 2020). The majority of the country's producing mines are owned by Chinese companies (Darton Commodities 2018)[1]. China's interest in cobalt mining and refining stems from its dominance in LIB manufacturing and related priority to secure the supply chain.

Given the highly concentrated market within the country, cobalt supply is greatly affected by the security of the DRC, which according to the World Governance Indicators is one of the most politically unstable and corrupt countries in the world. In 2020, the World Bank Group ranked DRC in the lowest 10th percentile in terms of political stability, governance effectiveness, rule of law, and control of corruption (Olivetti et al., 2020). Civil war and health crises directly influence mining

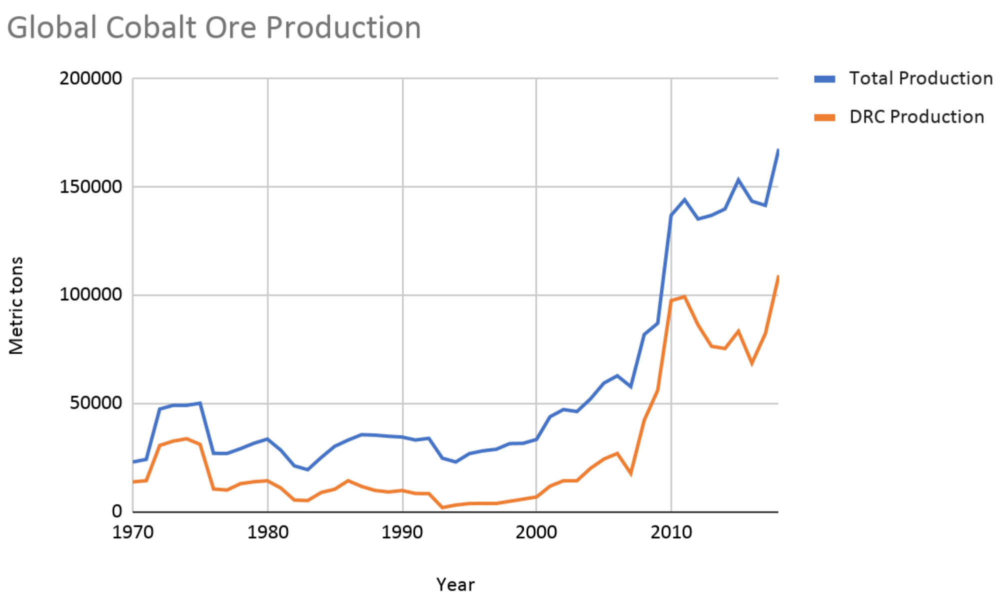
[1] Some of the Chinese companies operating in the DRC include China Molybdenum Co., Ltd., Zhejiang Huayou Cobalt, Jinchuan Group, Shalina Resource, Wanbao Mining, and Nanjing Hanrui Cobalt.

capacity and productivity (Van den Brink et al., 2020). In 2016, violence in the Kasai region (where most of the mine workers come from[2]) escalated due to a local dispute between a chief and the national government (World Vision, 2018). Notably, there was a drastic drop in DRC cobalt production in the same period. Moreover, according to Bloomberg, the DRC has deemed cobalt to be of strategic interest and intends to more than double the taxes applied to cobalt exports, which could lead to an aggressive increase in the commodity price. A growing number of end consumers declared that they will not source cobalt from conflict zones or from artisanal mining in which a prevalent and unethical use of child labor has been identified (Amnesty International, 2017). Thus, the insecurity of DRC represents a potential major constraint in cobalt supply.

A study commissioned by the European Union in 2018 estimated that the production capacity of cobalt from operating mines worldwide is currently 160,000 tons. By 2030, this capacity is expected to increase to between 193,000-237,000 tons if additional exploration projects under late-stage development are considered (Alves Dias et al, 2018). While these projects are expected to introduce significant amounts of cobalt into the market within the next decade, additional supply is most likely to stem from the expansion of existing producers such as the DRC. Moreover, existing research predicts that low cobalt-producing countries such as Australia and Canada which currently account for less than 7% of overall cobalt production are expected to gain importance, which may help to reduce the concentration of supply and disruption risk by 29% by 2030 (Alves Dias et al., 2018).

[2] especially child labor, https://minorityrights.org/trends2020/drc/

Figure 1. Cobalt production share from 1970 to 2018. (Data source: British Geological Survey World Mineral Statistics Database).



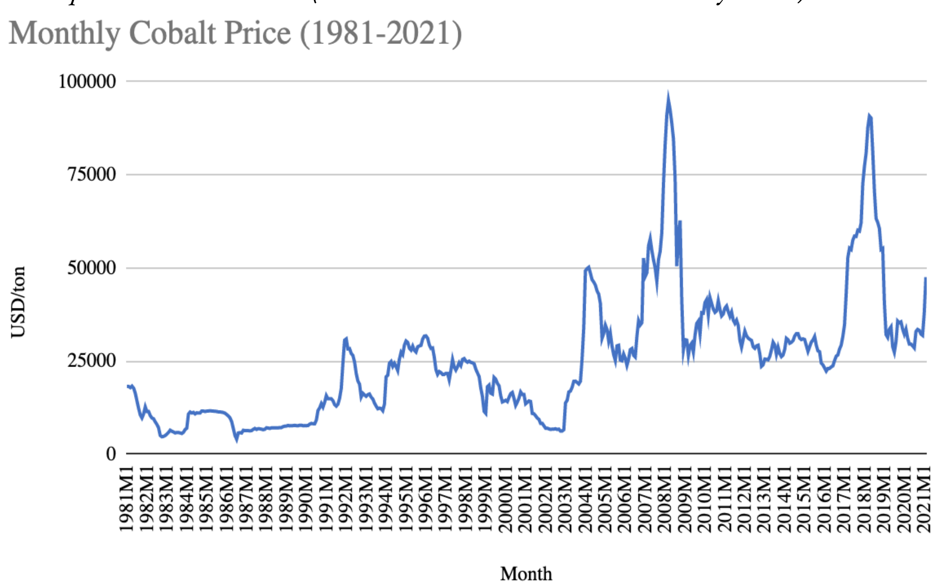
Cobalt Demand

Cobalt is predominantly used in chemical applications (e.g., batteries and catalysts), and metallurgical applications (e.g., superalloys). Cobalt's unique magnetic and metallic properties limit its substitutability and render its demand in the aerospace, defense, energy, oil, and gas industries highly price inelastic (MIT, 2018). The recent growth of the electric vehicle sector has driven higher demand for lithium-ion batteries, which has in turn created an increasing demand for cobalt. In 2016, about 40% of total global cobalt production was employed in manufacturing LIB cells while 60% for catalysts and superalloys. The demand for LIB for electric vehicles increased by 191% in the 2014–2016 period, from 11,000 MWh to 32,000 MWh (NREL, 2019). Concurrently, the proportion of global cobalt consumption accounted for by electric vehicles increased from 1.4% to 5% of total mine production. As of 2020, China remained the leading consumer of cobalt used to manufacture cathode active materials for LIB. The U.S., Japan, and the Netherlands are the other primary importers of cobalt. Global cobalt demand has been reported as increasing from approximately 40,000 metric tons in 2000 to almost 140,000 metric tons in 2019 with a compound annual growth rate (CAGR) of more than 6%. Such a large annual growth rate indicates that there are reasonable concerns that individuals, companies, and governments have regarding the future supply and demand of cobalt.

Cobalt Pricing

Only in February 2010 did the London Metal Exchange (LME) begin trading cobalt at its metal exchange. Previously, cobalt was traded in an over-the-counter market with few companies displaying cobalt prices (Ecorys, 2012). The price trend of cobalt appears extremely volatile (variance of 297241592 and standard deviation of 17241 for a mean value of 25222.86386 USD/ton) as shown in *Figure 2*. Since 2000, cobalt demand has risen progressively, though the price has proven to be more unpredictable than consumption given shocks in both demand and supply. Strong demand for rechargeable batteries, initially used in electronic equipment, has been the chief driver of growth. According to a report commissioned by the U.S. Geological Survey on critical materials influencing factors, the price has varied in response to general global economic conditions, supply and demand fundamentals, and several other factors of relatively short duration. Political and economic instability and civil unrest in the DRC have long influenced global cobalt supply and therefore prices (Papp., et al, 2008). Other factors that have proven influential at various times include cobalt sales from the United States' government stockpile and increased supply of cobalt from Russia following the break-up of the Soviet Union in 1991 (Alves Dias et al., 2018). In 2003, cobalt prices increased sharply in response to reduced production and concerns over tightness in global supply. During the commodity boom that followed, prices continued to rise, peaking in early 2008 close to $110,231 USD per metric ton (BGS, 2020). In response to the global financial crisis and economic downturn, cobalt demand fell drastically, and prices plummeted to below $28,660 USD per ton in December 2008. While growing battery demand and supply concerns catalyzed a short-term uptick during 2009, cobalt price followed a general downward trend between 2010 and late 2016. In March 2018, price rose to a near-decade high, with an average price in the second quarter of nearly $94,798 USD per ton. This substantial increase is attributed to strong demand from consumers in China for rechargeable batteries, combined with concerns about mine production from the DRC and availability from refineries in China. Following this peak, the price fell 60% in the following year due to increased supply from mines in the DRC together with reduced demand for EV batteries in China. Cuts to subsidies on EV sales in China, announced in March 2019, have further negatively impacted demand (BGS Commodity Review, 2020).

Figure 2: historical price trend of cobalt. (Data source: International Monetary Fund)



Cobalt Recycling

Recycling can play an important role in determining cobalt supply, but there are associated challenges and barriers to overcome both in the short and long term. Successful recycling of cobalt is driven by a number of parameters including battery lifespan, end-of-life regulations, price of battery metals, and global recycling capacity. Cobalt alloy scrap and spent rechargeable batteries are the two most important streams of secondary cobalt supply. The recycling of rechargeable batteries is complex due to the wide range of battery types and their different chemistries and forms. The major methods involve mechanical recovery, pyrometallurgy, hydrometallurgy, and combinations of these processes. Recycling of spent batteries is mainly taking place in Europe[3], where more progressive environmental regulations such as the Green Deal have been put in palace (BGS Commodity Review, 2020). Cobalt is not the only metal contained within scrap, and the economics of recycling will be affected by the presence or absence of other metals of interest and the prices of those metals. Inefficiencies in the collection of batteries result in low collection rates, which in turn adversely affect the viability of the metal recycling sector. As the market of exhausted EV batteries becomes significant, recycling could represent a valid and more sustainable alternative to cobalt mining. The global LIB recycling market size is projected to reach USD 19380 million by 2026, from USD 2794.4 million in 2020, at a CAGR of 38.1% during 2021-2026 (PR Newswire, 2020). Major factors driving the growth of the Lithium-

[3] Locations: Belgium (Umicore), Germany (Accurec Recycling GmbH), France (Valdi), Switzerland (Batrec Industrie AG), Norway (Glencore–Nikkelverk), Finland (AkkuSer Oy)

ion battery recycling market size are increased automotive battery usage, strict government regulation about battery disposal, and a surge in smartphone penetration and laptops.

III. Literature Review

Given the recent shock in cobalt demand stemming from Li-ion batteries and its concentrated supply, numerous studies have attempted to predict the future of the cobalt market. Several methods have been used to forecast quantity produced; from bottom-up analysis of end-uses, to supply scheduling, to price elasticities estimations. Market studies and forecasts focus more on the assumptions underlying market segment development such as end-uses growth, battery chemistry, the lifetime of batteries, and regulations. Econometric papers such as CBO (1982) and Gupta P.& S. (1983), on the other end, aim to calculate the responsiveness of market players to cobalt price changes through the estimation of price elasticities. This paper is an attempt to bring together the more market-like supply-demand forecast modeling and the econometric calculation of price elasticities to estimate cobalt market balance in 2030. The focus is on a mid-term projection (2030) rather than an attempt to capture short-term market price volatility. I begin with a review of the previous efforts to calculate price elasticities of demand and supply for commodity metals.

A number of empirical studies estimate demand and supply focusing on commodity price elasticities over time. These estimations find a variety of applications in commodity pricing forecasting and policy analysis. Different models may be appropriate given the available data and the purpose of the model. Researchers are typically interested in deriving short-run and long-run price elasticities and their standard errors. A substantial number of papers have used a variety of models to estimate demand elasticities, as they are a convenient way to summarize the responsiveness of demand to commodity price (Dahl, 1993). CBO (1982) and Gupta P.& S. (1983) used a single-equation data generating process by assuming a perfectly elastic supply of energy. Supply of electricity, gas, and similar energy products are considered to be built for the only purpose of serving energy consumption and are therefore assumed to have a price elasticity of 1. In the case of cobalt, however, the metal is a by-product of nickel and copper, which makes its supply exogenous and therefore less responsive to changes in the price of cobalt. As Andrew Harvey (1990) emphasized: "Econometric models typically consist of sets of equations which incorporate feedback effects from one variable to another. Treating the estimation of a single equation from such a system as an exercise in multiple regression will, in general, lead to estimators with poor statistical properties." For such a reason, estimating supply-side price elasticity is also needed to best identify the global cobalt market.

Cuddington et al. (2015), in a review of energy demand estimation, revealed two common deficiencies in demand elasticity modeling: 1) the omission of standard errors when reporting short-run and especially long-run elasticities and 2) the use of restricted models without testing the relevant restrictions (Cuddington et al., 2015). The paper suggests that a general autoregressive distributed lag model, assuming serial uncorrelated error terms, should be employed in the estimation of demand elasticities. Another model used to correctly estimate standard errors is the simultaneous equations system. In this model, supply and demand are estimated simultaneously and at least one equation in the model is estimated using exogenous variables (instrumental variables). A first intuition of using instrumental variables to assess price elasticities to estimate the short and long run demand elasticities with respect to price for various cobalt end uses in the U.S. was presented by Gupta P.& S. (1983). The instruments selected to identify demand are U.S. government stocks of cobalt and U.S. government net purchases of cobalt. The results indicated that the long-run price elasticity in all cases was greater than the short-run elasticity. Largely due to reasons of data availability, the estimation is annual and end-use analysis has been restricted to the U.S. For this reason, the demand elasticities estimates cannot represent global demand. As the authors noted, it is difficult to access data on each country's cobalt end-use demand. However, to attempt to identify global price elasticities, this paper will assume a zero supply-demand balance, using yearly cobalt production data as a proxy for global cobalt annual consumption.

This technique was employed in a recent Duke University Economics honor thesis titled "*Identifying Supply and Demand Elasticities of Iron Ore*" (Zhu, 2018). Zhu compared the use of ordinary least squares (OLS), two-stage least square (2SLS), and three-stages least square (3SLS) models to identify elasticities of demand and supply for iron ore. As proved in the paper, estimating supply and demand functions through OLS lacks both identification and efficiency (Goldberger, 1991) while 2SLS and 3SLS accounts for the correlation between the error terms across the equation. Price elasticities of cobalt supply and demand can be derived from such a model. Although Zhu's paper was useful in defining the methodology to estimate price elasticities, a deeper look into the specific estimation of cobalt elasticity was needed to set comparables for final results.

The Congressional Budget Office (CBO) (1982) published figures for cobalt demand price elasticity for each end-user segment (namely jet engines, electrical components, mechanical components, and non-metallic uses). The overall long-run elasticity of demand for cobalt is estimated to be approximately -0.32. This means that a 1.0 percent increase in the price of cobalt would cause its consumption to drop by 0.32 percent. Back in 1982 however, Li-ion batteries were not yet commercialized and therefore not accounted for as a consumption segment. The introduction of the new battery end-use started in the late nineties when smartphones started to shift away from the less energy-dense nickel batteries. Additionally, the CBO paper is limited to the calculation of the price elasticity of demand but does not investigate the supply curve. However, the CBO's analysis is a useful comparison to the results of this paper.

Drawing from the literature identified above, this study will use the most recent data on cobalt price and production to run a 3SLS model of simultaneous equations identified by a set of instrumental variables to define cobalt global supply and demand function. Findings from empirical studies that determined the relation between cobalt price and external factors informed the identification of instrumental variables. USGS (2008) identified macroeconomics factors such as global GDP and interest rate as determining factors of cobalt price and price volatility. Zhao et al (2020) included trade positions and closeness of countries as statistically significant drivers of mined cobalt price. Finally, Renner et al. (2019) used the 1978 Shaba crisis in the DRC to show that civil conflicts cause supply interruptions that increase cobalt price. A measure of global GDP, interest rate, DRC copper production, and DRC conflicts should therefore help correctly identify the cobalt demand and supply trends.

In the general literature, the estimated elasticity coefficients are employed to simulate market forecasts to speculate on the future price and quantity produced. Usually, a mean value is selected for each independent variable of the model, and price and quantity are calculated accordingly. However, as numerous cobalt-focused papers discuss, the future of the global cobalt market will be dictated by variables that historically have been statistically insignificant (or just introduced too recently in the market) such as the sales of electric vehicles and the rampant improvements in battery chemistry. For this reason, a short review of the cobalt market papers is necessary in order to make adjustments to the forecast model that is the outcome of this study.

Olivetti et al. (2020) performed a simulation of 2030 supply and demand summing compounded annual rates of each end-use segment and supply source. The authors forecasted how primary and secondary supply (i.e., recycling) will need to adjust to meet the changing demand. The results estimate a demand of 235,000 to 430,00 metric tons for cobalt in 2030, but only 188,000 to 368,000 tons production from mining. The paper suggests that the only way to address the supply shortage is to introduce Li-ion batteries recycling as a new source of supply and tap into alternative cobalt reserves such as the seafloor stock. As presented by the authors, the growth in demand depends on the compound annual growth rate (CAGR), market growth rate, and cathode chemistry. The paper suggests that cobalt price will remain stable in the short run and supply and demand will be balanced. However, changing the assumption around CAGRs results drastically change. In a thorough effort to quantify supply and demand balances, Dias et al. (2018) placed several assumptions around the future shift in cobalt primary production. Through statistical analysis, the authors forecasted future technological changes in mining, artisanal mining capacity, and unannounced projects. Sensitivity analysis is performed, and the results indicate that demand will exceed supply from 2027 (Dias et al, 2018).

Although a useful framework for my cobalt market forecast exercise, such papers' limitations lay in the estimation of supply and demand as separate from each other. I believe that suppliers and demanders respond to price signals and that the interaction effect between production and consumption should be modeled. Therefore, to further increase the preciseness of my model and better identify the future quantity and price of cobalt in light of projected demand, I will combine the use of simultaneous equations to estimate elasticities of demand and supply with the assumptions around future technological changes in the supply curve.

IV. Theory

In this section, I describe the global cobalt supply-and-demand model and explain each of the instrumental variables included in the equation. To correctly run the forecast exercise, later explained in the *Empirical Methodology* section, the slopes of the supply and demand curves need to be determined. I begin by explaining the use of the 3SLS model and indicator variables to calculate price elasticities of supply and demand.

Method for efficient identification of supply and demand

The term three-stage least squares (3SLS) refers to a method of estimation that combines system equations with two-stage least squares estimation. It is a form of instrumental variables estimation that permits correlations of the unobserved disturbances across several equations, as well as restrictions among coefficients of different equations, and improves upon the efficiency of equation-by-equation estimation by taking into account such correlations across equations. Unlike the two-stage least squares (2SLS) approach for a system of equations, which would estimate the coefficients of each structural equation separately, the three-stage least squares estimate all coefficients simultaneously (Encyclopedia, 2021). 2SLS and 3SLS are more efficient methods as both use identificatory variables to discern supply and demand (Zhu, 2012). Zhu, additionally, suggested a reason for the selection of 3SLS over 2SLS; the three-stage least square method generalizes the two-stage least-squares method to take account of the presence of the correlation between residual terms in structural equations of supply and demand. The tradeoff between 2SLS estimates for supply and demand equations and 3SLS estimates is that if the model is correctly specified, 3SLS estimations are superior because of increased efficiency (need fewer observations than a less efficient estimator to achieve a given performance). However, if one equation (e.g. supply equation) is miss-specified, this miss-specification negatively impacts the 3SLS estimate of the parameters in the other equation (e.g. demand equation) (Zhu, 2012). Equations that are under-identified are disregarded in the 3SLS estimation. (Encyclopedia, 2021)

Instruments Selection

In general, a valid instrument should meet three requirements (Goldberger, 1991):

1. The instrument must be correlated with the endogenous variable (Pt), conditional on the other covariates.

2. The instrument cannot be correlated with the error terms (μt and νt) in the explanatory equation.

3. Exclusion should also be applied when instrumental variables are selected to differentiate the supply and demand equations.

I begin with the selection of indicators in the cobalt demand equation to create the model. In general, economists assume that variables correlated with income and consumption are exclusive variables of demand. A good estimate of the growth rate of global income and output is the real-world GDP. Therefore, I selected world GDP as an instrument of demand. Since an increase in world GDP leads to an increase in the global sales of electronics and superalloys, I expect the coefficient for GDP on price to be positive. The introduction of technological changes in the battery industry represented a shock in cobalt demand. Significant ramp-up of demand started in 2016 after the boom in portable devices battery and the beginning of EV scale-up manufacturing. An EV stock variable can capture the outward shift of the demand curve. I expect the coefficient for EV stock on price to be positive.

To identify the supply equation, I start by using the Hotelling rule which includes interest rate in the supply function. According to Hotelling's rule, a commodity stored underground can be regarded as a capital asset (Hotelling, 1931). The commodity owner has two options, either to sell the product or to postpone its sale and keep underground inventories (Zhu, 2012). Traditionally in a Hotelling model, the relationship between price and interest rate is negative, but that is because a higher interest rate causes an increase in extraction today (extraction in the future is worth less so the owners are incentivized to extract today). Increasing extraction today means an increase in quantity supplied and a decrease in equilibrium market price all else equal based purely on Hotelling theory. However, higher interest rates also mean higher capital costs and higher capital costs are a supply constraint (equipment is more expensive to buy or rent). Therefore, an increase in interest rate can also cause a countervailing effect which raises the marginal cost of mining today and therefore reduces the quantity extracted. Accordingly, a higher interest rate has an ambiguous effect on the quantity supplied. Cobalt is a by-product of copper mining, so its production can be a significant indicator of cobalt supply. The big part of copper and cobalt production is located in Congo, therefore a variable to account for DRC copper production will be used to identify global cobalt supply. I expect an increase in Congolese cobalt production prices to be positively correlated to cobalt supply. A unique feature of cobalt supply is its dependence on DRC internal conflicts. I will use a dummy variable to explain the shock in supply that derives from conflicts. Finally, it is worth noting that for my long-term structural model I am not including a price lag variable P(t-1) as the annual price variable already accounts for yearly price variability.

In summary, the supply and demand log-linear equations are the following:

Demand:

$$\ln(Q_{tD}) = \beta_0 + \beta_1 \ln(P_t) + \beta_2 \ln(World\ GDP_t) + \beta_3\ (\text{Mobile Subscriptions}) + \mu$$

(III.1)[4]

Supply:

$$\ln(Q_{ts}) = \gamma_0 + \gamma_1 \ln(P_t) + \gamma_2 \ln(\text{Interest Rate}_{\ t}) + \gamma_3 \ln(\text{DRC Copper Production}_{\ t}) + \gamma_4\ (\text{DRC Conflicts}_{\ t}) + v$$

(III.2)[5]

where the market-clearing condition is:

$$Qts = Qtd$$

(III.3)

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4 P= Average cobalt yearly price (USD/ton). World GDP= total annual global output. Mobile Subscriptions= total annual mobile phone descriptions, a proxy of phones sold.

5 P= Average cobalt yearly price. Interest Rate= U.S. 10-year Treasury Yield. DRC Copper Production= total annual prediction of copper in Congo. DRC Conflicts= dummy for armed conflicts in Congo (where 0 is no major conflicts and 1 is >1 conflicts in the Congolese territory that year.

The long-run price elasticities of supply and demand are identified by the following equations:

$$\frac{\partial Q_D}{\partial \mathrm{P}} = \beta_1$$
$$\frac{\partial Q_S}{\partial \mathrm{P}} = \gamma_1$$

(III.4)

IV. Empirical Methodology

Even though the cobalt market has characteristics of both oligopoly and monopolistic competition, I believe the underlying price can still be determined by the interaction of fundamental demand and supply. Therefore, for this paper, I attempt to estimate the cobalt market based on the perfect competition model in which the market price acts to equilibrate supply and demand in the long term. However, it is worth noting that the cobalt market has characteristics of an oligopsony, with few buyers and few suppliers as described in the introduction section. The use of a supply-demand model simplifies the market competition and will likely not fully capture the dynamics of cobalt ore price setting. This paper intentionally avoids the study of monopolistic behavior as it would involve game-theory models that go beyond the scope of this honor thesis.

To forecast cobalt price and quantity in 2030 after the introduction of recycling, 2018 world cobalt ore price and quantity, the most recent available data, are set to be the starting partial equilibrium point. The reported average price in 2018 was 72,911.237 USD/ton and the produced quantity amounted to 167,801 metric tons (BGS, 2021).

The second step of the forecast exercise is to project the estimated supply and demand equations in 2030 and study the market equilibrium. According to the projected growth rates of the demand drivers, such as EV vehicles, the world's GDP, and global mobile subscriptions, overall demand is expected to drastically increase by 2030. According to partial equilibrium theory, a boost in demand will drive prices up and will be followed by an adjustment in supply in the long-term model. With no other conditions in the market changing, the equilibrium point reflecting the demand shift in 2030 can be calculated.

This paper aims to quantify the effect that the introduction of battery recycling (or of a supply shock) will have on the 2030 market equilibrium. To account for the technological change coming from battery recycling, a new supply source, with a different marginal cost, is added to the existing supply stock function coming from mined cobalt. The magnitude of the supply shock depends on various variables such as recycling policies, collection rate, battery chemistry, and battery lifetime. According to Olivetti (2020), the magnitude of the secondary supply shock is based on two main assumptions. First, the lifetime of the product, which is a proxy for when the exhausted battery will be able to circulate back in the supply market. Secondly, the collection and recycling rate, which are a proxy of how much of the mined cobalt will be recovered from the exhausted batteries and sold as a substitute for the metal itself.

A parametrization of the new supplied quantity can be identified as follows:

New Quantity Supplied= Quantity mined + Quantity recovered from exhausted batteries

(IV. 1)

where the quantity of cobalt recovered from exhausted batteries is equal to:

Quantity recycled= (Number of Exhausted Electric Vehicles x EV Cobalt Content x Collection Rate x Recycling Rate) + (Number of Exhausted Smartphones x Smartphones Cobalt Content x Collection Rate x Recycling Rate)

(IV. 2)

To more precisely account for the magnitude of the effects of recycling on the cobalt market, supply and demand curves will need to be identified. Predictively, the introduction of recycling technologies will shift right the supply curve and make cobalt more economical. In this study, I assume that the marginal cost of recycling[6] will be always lower than the market price of cobalt, therefore all recovered cobalt will be sold economically. Moreover, I believe that the burden of recovering metals from exhausted batteries will be put on EVs and smartphone manufacturers that will be increasingly demanded to take care of the full supply chain of their batteries, as announced in the EU Green Deal regulation. For such reasons, the marginal cost of producing recycled cobalt will be reduced by the cost associated with infringing recycling regulations. This study will leave to further research the parameterization of the recycling cost and will more simply assume throughout:

MC(recycling) < Cobalt Price

(IV. 3)

[6] Recycling cost numbers were calculated using the Everbatt Model from the Argonne National Laboratory, a more thorough explanation of its calculations can be found in *Appendix 1.*

V. Data

I begin with a preliminary examination of the variables included in my annual supply-demand model. Figure 3 presents time-series plots of the six variables used in my simultaneous equations model. Summary statistics of all annual variables are presented in Table 1. The predicted effects of each variable on cobalt supply and demand are summarized in Table 2.

Cobalt's annual price was calculated as the average of the monthly US cathode spot prices recorded by the International Monetary Fund (IMF) each year. For the cobalt quantity series, I used global cobalt ore production data from the British Geological Survey (BGS) commodity database available in decade-long reports. A limitation of such data is that cobalt ore refers to the metal mined and does not have the same price of the refined cobalt (cobalt hydroxide) used by battery manufacturers. The mined cobalt ore quantity was used for identifying the demand curve, assuming market clearance's condition. World GDP was collected from the United Nation Conferences on Trade and Development (UNCTAD) database. Electric Vehicles car stock data are taken from the International Energy Agency (IEA) Global EV Outlook 2020. Federal Reserve Economic Data (FRED) U.S. 10-year treasury bill rate was used as the real interest rate as it represents the lowest-risk market rate. Congo's copper production quantities were extracted from the BGS mineral commodities report. Finally, data on DRC conflicts were transcribed in the form of a dummy variable from the Uppsala Conflict Data Program (UCDS) African conflicts database. A detailed explanation of the collection, clearing, and sorting of the data along with an instrumental-variables correlation matrix is provided in the appendix (Appendix 2, Appendix 3).

Table 1: Summary Statistics for annual data

Variable	Time	Mean	Median	S.D.	Min	Max	Source
Price and Quantity							
Real Cobalt Price (USD/ton)	1981-2018	24773	23056	16972	5876	72911	International Monetary Fund, Primary Commodity Prices[7]
Global mined cobalt production (tons)	1981-2018	64125	35665	47935	19597	167801	British Geological Survey, World Mineral Statistic Data[8]
Demand Shifters							
Real world GDP (trillion USD)	1981-2018	32	24	20	8	71	World Bank Open Data[9]
Global mobile subscriptions (billion)	1981-2018	2.2	0.6	2.8	0	7.9	World Bank, World Development Indicators[10]
Supply Shifters							
US treasury interest rate (%)	1981-2018	6	5	3	2	14	Federal Reserve Economic Data[11]
DRC copper production (tons)	1981-2018	378519	325850	356928	16359	1225227	British Geological Survey, World Mineral Statistic Data[12]
DRC conflicts (dummy)	1981-2018	0.5	0	0.5	0	1	UCDP data on Armed Conflicts[13]

7 https://www.imf.org/en/Research/commodity-prices
8 https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS
9 https://data.worldbank.org/indicator/NY.GDP.MKTP.CD
10 https://data.worldbank.org/indicator/IT.CEL.SETS.P2
11 https://fred.stlouisfed.org/series/DGS10
12 https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS
13 https://www.prio.org/Data/Armed-Conflict/

Table 2: Predicted effects of instrumental variables

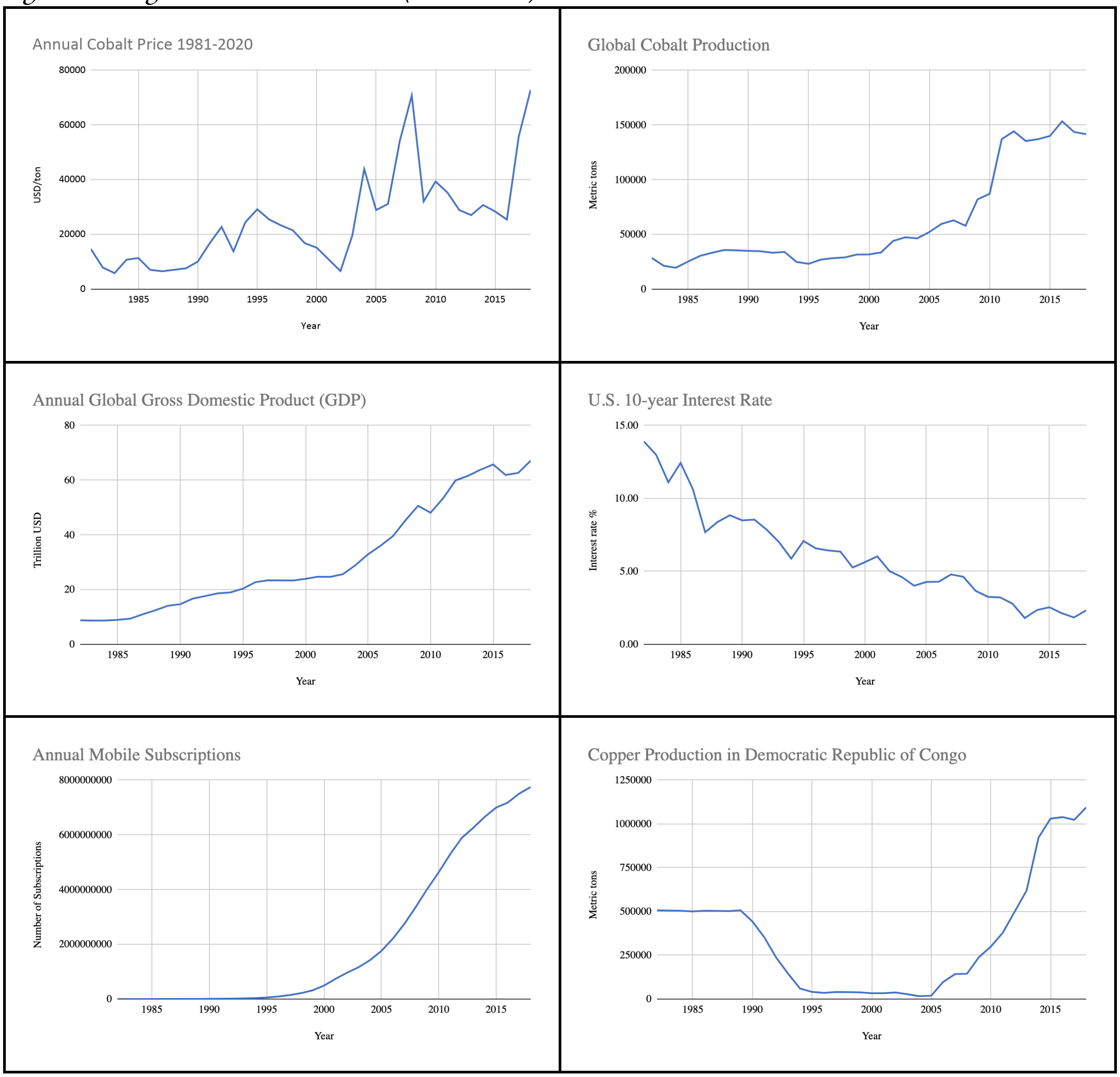
Exogenous Variable	**Predicted Effect on Demand/Supply**
Real world GDP	+, demand curve
Global mobile subscriptions	+, demand curve
US treasury interest rate	+/-, supply curve
DRC copper production	+, supply curve
DRC conflicts	-, supply curve

Figure 3 indicates the trends of each variable. World GDP and Global Cobalt production present a steady growth over the 38 years period between 1981 and 2018. Intuitively the two variables follow the trend of population growth. As the world becomes more populated overall consumption and outputs also grow. Mobile subscriptions follow the "S" trend also called the "technology curve", with slow initial growth, a sharp exponential increase in adoptions after 2000, and a slower growth starting from 2015 when the mobile markets started to be saturated. The U.S. Treasury 10-year rate sharply decreased since 1982 getting to all-time lows between 2011-2016. Annual cobalt price appears extremely volatile and presents cyclical spikes. Chinese demand for li-ion battery demand together with DRC political instability drove the price peaks in 2003, 2008, and 2018. Lastly, DRC copper production was steady in the 1980s and drastically dropped during the 1990s following a sharp decline in copper prices. Copper production in Democratic Republic of Congo picked up again in 2005 supported by legislative and political changes in the DRC[14] (Lydall et al., 2011). The reason for the

[14] A new mining code was established in 2003 and the first democratic elections took place in 2006

enduring spark in copper consumption is the growing demand for conductive wiring in low-carbon technologies, projected to continue to grow exponentially in the next few years.

Figure 3: Exogenous variables trends (1981-2018)



For the forecasting section of this paper, data on recycling, collection rate, and EV stock projections were collected. Table 2 presents a summary of the variables. Projections of electric vehicle stock were taken from the International Energy Agency Global Outlook 2020. Numbers for battery collection rates were assumed to comply with the Green Deal's goals as announced in the European Union Sustainable Battery Regulation. The percentage of cobalt contained in the battery was calculated as a standard NMC (1:1:1) battery and taken from comparable industry studies. Battery lifetime, used to identify the new cobalt stock coming from recycling, was calculated as an average of li-ion batteries from data of the Committee on Energy and National Resources. The global GDP figure for 2030 was taken from the E.U. report "The Global Economy in 2030". The interest rate was estimated to be at the long-term average level presented in the Federal Reserve Economic Data. DRC Copper production was estimated at a compounded annual growth rate of 20%, according to the average 3-years growth from the British Geological Survey data. Finally, DRC conflicts were kept at the average level between 1970 and 2018.

Table 2: Summary of Simulations Assumptions

Market Variable	2030 projection	Source
Exhausted EVs	3.27 million	International Energy Agency, Global EV Outlook 2020[15]
Battery Cobalt Content (NMC)	12 kg	McKinsey, *Lithium and Cobalt* report[16]
Smartphones Cobalt Content	6.3 g	Buchert et al., 2012
Battery Average lifetime	12 years	Olivetti et al., 2020
Collection for EV batteries	100%	EU Sustainable Battery Regulation, Green Deal[17]
Collection Smartphones	70%	EU Sustainable Battery Regulation, Green Deal
Recycling Rate	90%	Nth Cycle Proprietary Technology[18]
Exogenous Variable	2030 projection	Source
World GDP	USD 130 trillion	European Union, *The Global Economy in 2030*[19]
World Mobile Subscriptions	8.5 trillion	World Development Indicators[20]
Interest Rate	4.37%	Federal Reserve Economic Data
DRC Copper Production	158968716.3 tons	British Geological Survey, World Mineral Statistic Data
DRC Conflicts	0.3	UCDP data on Armed Conflicts

15 https://www.iea.org/reports/global-ev-outlook-2020

16 https://www.mckinsey.com/industries/metals-and-mining/our-insights/lithium-and-cobalt-a-tale-of-two-commodities

17 https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2312

18 https://nthcycle.com/battery-recycling/

19 https://espas.secure.europarl.europa.eu

20 https://datacatalog.worldbank.org/mobile-cellular-subscriptions-0

VI. Results

I first start outlining the results of the 3SLS model to identify price elasticities of supply and demand. I then use the coefficient obtained to project the 2030 market equilibrium with and without recycling.

Demand and Supply Estimation

Estimations of the long-term structural equations (III.1 and III.2) are summarized in Table 4.

Table 4: Stata Output of 3SLS regression

VARIABLES	(1) Quantity Demanded	(2) Quantity Supplied
Ln (Cobalt Price)	-0.230***	0.136***
	(0.0776)	(0.0468)
Ln (DRC Copper Production)		0.150***
		(0.0183)
Ln (Interest Rate		-0.929***
		(0.0610)
DRC Conflicts		-0.0891*
		(0.0462)
Ln (World GDP)	2.122***	
	(0.186)	
Ln (World Mobile Subscriptions)	-0.200***	
	(0.0302)	
Constant	9.957***	9.214***
	(0.591)	(0.618)
Observations	38	38
R-squared	0.915	0.950

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Under the 3SLS, all the instrumental variables used are robust indicating that the instruments selected are strong and reliable. Additionally, overidentification problems are excluded through the chi-squared test of restriction results[21]. According to economic theory, the coefficient of price is negative in the demand equation and positive in the supply equation, in agreement with the initial hypothesis. Both the supply price elasticity and the demand price elasticity coefficient are significant at the 0.1% level. The price elasticity of demand is -0.230 indicating that cobalt ore is price inelastic. Compared to the -0.32 demand elasticity calculated by CBO econometric modeling in 1982, cobalt demand seems more price inelastic. The introduction of battery cathode as a new end-use of cobalt around the 1990s can explain the increase in inelasticity. The price elasticity of the supply of cobalt ore is 0.136, indicating an extremely price inelastic supply. The magnitude of the number can be explained by the characteristic of cobalt production, mainly produced by DRC as a by-product of copper and nickel. Intuitively, even if the demand for cobalt will drop, the producers will continue to mine the ore to satisfy the demand from other metals. From the model, we can deduce that the supply curve is more price-inelastic than the demand and of a steeper slope. This shows that demanders are more price-sensitive than suppliers, and therefore more inclined to look for substitutes.

In the demand equation, World GDP has the expected positive coefficient while global mobile subscriptions have a negative coefficient. Both are statistically significant at the 0.01% confidence level. As hypothesized in the theory section, higher world output leads to a higher demand for cobalt as a growing economy will request more smartphones, engines, vehicles. Against my expectations, the coefficient for mobile subscription is negative. These results could be explained by the high correlation between GDP and mobile subscriptions and the long term tendency of electronics manufacturers to

[21] Test of overidentifying restrictions: Demand: Score chi-squared= 215.49 (p=0.0000), Supply: Score chi-squared= 752.16 (p=0.0000)

shift away from cobalt-heavy batteries. For future studies, the demand equation should include a measure of nickel battery sales, the main competitor of li-ion batteries, that could better identify the shift in cobalt demand. An indicator of superalloys and catalysts end-uses can also improve the estimation. Finally, as EV sales become more significant, it will be useful to include such variables in the regression to capture the most recent growth in demand. Given the lack of publicly available historical data, this study was not able to include such variables.

In the supply equation, DRC Copper Production, and DRC conflicts have the expected coefficient signs and are statistically significant at the 0.01%, 0.01%, and 0.1% confidence level. The negative coefficient for interest rate indicates that a rise in the cost of capital will disincentivize producers to extract more cobalt as the cost of capital (equipment) is higher. Congolese copper production is positively correlated with supply as hypothesized. Finally, the DRC conflict coefficient is negative supporting evidence of supply interruption during periods of civic conflicts in Congo. The 3SLS model's R-squared ranges from 0.91 to 0.95, indicating a good predictive power and high overall fit despite the limited availability of the sample size (total of 38 observations). The general standard 3SLS model averages 150 observations (Zhu, 2012), therefore the results of my regression should be interpreted carefully. The goodness of fit was also verified with a chi-square test. Both the demand and supply's chi-squares have p-values of 0, indicating a strong predictive power of the model. Finally, the Durbin-Watson test value indicates autocorrelation among independent variables.

However, the 3SLS D value equal to 0.76 is smaller than the lower-bound D-statistics of 0.913[22], rejecting the hypothesis of serial correlations in the residuals at a 1% confidence level. For future studies, a monthly model will be preferred to provide more data points and a better estimation of the demand and supply curve.

From the results of Table 4 we derive the following equations:

Demand:

ln(Qd)= 9.957-0.230*(ln_price)+2.122*ln(gdp_w)-0.200(ln_mobilesub) (VI.1)

Supply:

ln(Qs)= 9.214 +0.136 *ln(prce)+ 0.150*(ln_drccuprod)-0.929*ln(intrate) -0.0891*drc_conflicts (VI.2)

Forecast

The supply and demand equations estimated above are used to forecast the 2030 market equilibrium forecast. The initial equilibrium in 2030 is performed assuming specific values for each of the seven exogenous variables presented in (Table 2) of the empirical methodology section. A summary of equilibrium price and quantity is presented in Table 3.

[22] For the 3SLS regression with 7 independent variables and 38 observations, D statistic ranges from 0.913-1.735. d statistic was calculated using Durbin-Watson table https://www.real-statistics.com/statistics-tables/durbin-watson-table/

Table 5: summary results for market equilibrium quantities

Year	Price (USD/ton)	Quantity (metric tons)
2018	79,311	141,749
2030 without recycling	856,208	287,510
2030 with recycling	485,728	327,512

	Quantity % change	Price % change
2018-2030 w/out recycling	+103%	+980%
2018-2030 with recycling	+131%	+512%
2030 after recycling	+14%	-43%

To find optimal cobalt price and quantity level in 2030 we set:

$$Qs = Qd \tag{VI.1}$$

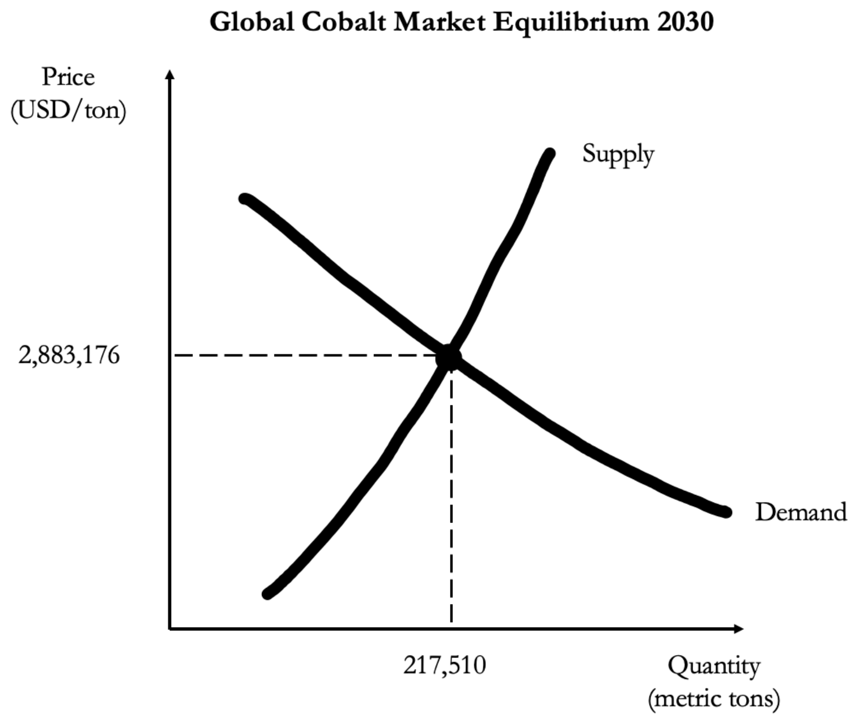
The full equation is the following:

9.957-0.230*(ln_price)+2.122*ln(gdp_w)-0.200(ln_mobilesub)= 9.214 +0.136 *ln(prce)+ 0.150*(ln_drccuprod)-0.929*ln(intrate) -0.0891*drc_conflicts

(VI.2)

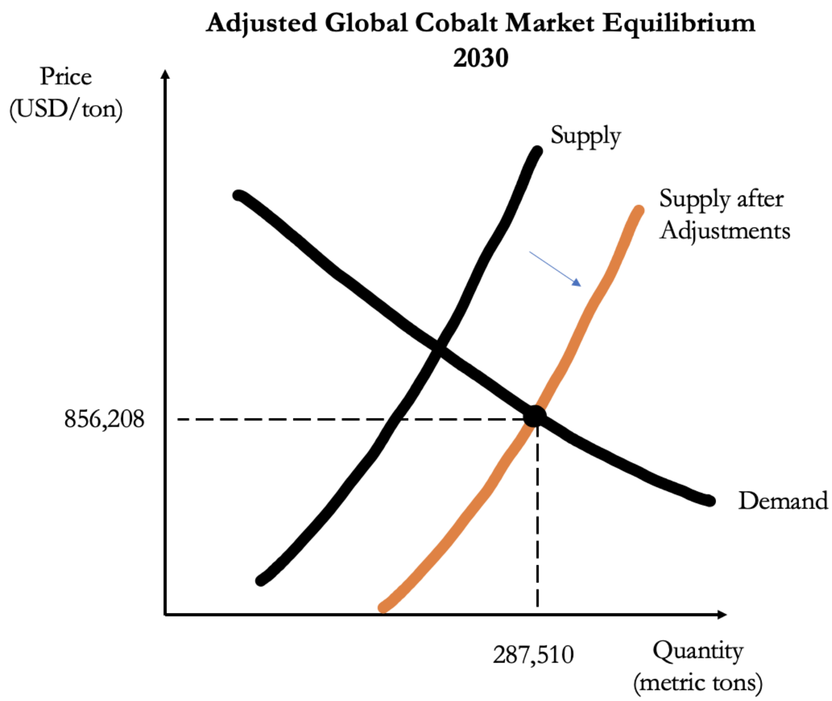
where the price is unknown. Solving for price in 2030 gives a cobalt quantity of 217,510 metric tons and a price of USD 2,883,176 a ton at market equilibrium (Figure 4).

Figure 4: estimated global cobalt market equilibrium in 2030



However, the identified supply and demand coefficients do not take into account the technological changes that could affect supply. Therefore, an adjustment in the supply curve is needed to better estimate global cobalt market equilibrium in 2030. Specifically, an exogenous shift in the supply curve will be driven by deep-sea mining projects and efficiency gains. Beginning in the mid-2020s there may be up to five contractors able to extract cobalt from the underwater reserves resulting in around 6,000 tons per year per contractor (Olivetti et al., 2020). Considering that such mining projects will be running in 2030, an additional 30,000 tons of cobalt should be added in 2030. Improvements in extraction efficiency should also be accounted for in the 2030 equilibrium. Assuming a 95% recovery in primary mines and 80% in by-product mines. an additional 40,0000 tons of cobalt ore can be added to the supply (Olivetti et al., 2020). Summing up the two exogenous shocks in supply, quantity in 2030 would be boosted by 70,000 ton as shown in Figure 5 achieving a market equilibrium of 287,510 metric tons of cobalt produced at a price of USD856,208 per ton.

Figure 5: estimated adjusted global cobalt market equilibrium in 2030

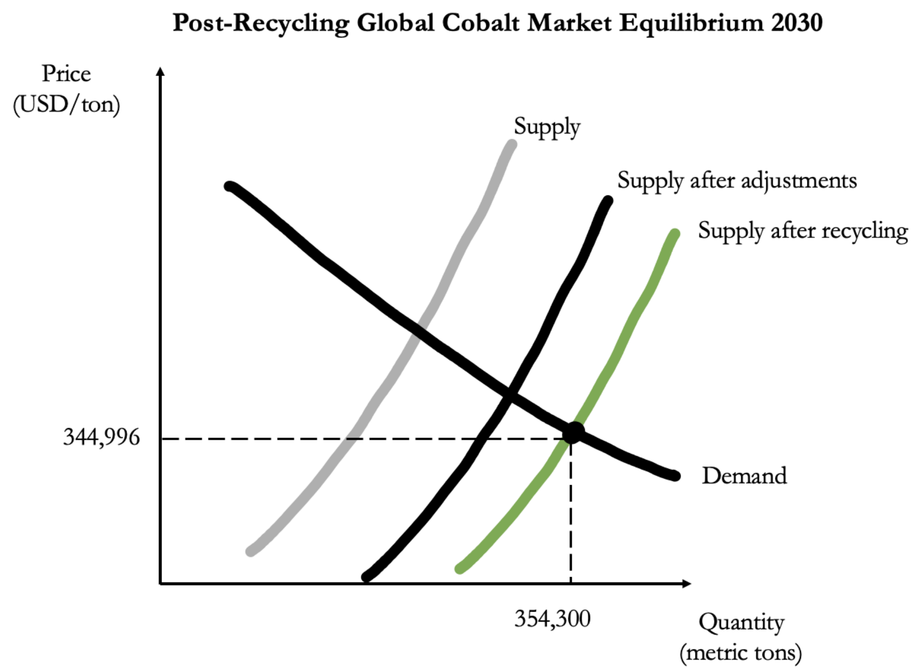


Given the underlying assumptions, the cobalt price would increase by 980% from 2018 to 2030 while the quantity increases by 103%. As shown above in the 3SLS results, in the cobalt market it takes a significant price increase to mobilize the extremely price inelastic supply. Overall, the forecast presents a worrying scenario for the battery market. Under the assumed conditions, the extremely high cobalt price (more expensive than gold) will be a limiting factor for the sustainable production of li-ion batteries. However, if alternative sources of supply arise (i.e. more primary cobalt mining, significant deep-sea extraction, and recycling) the supply might be more responsive to price changes and directly mitigate the sharp boost in price. It is highly unlikely that this market equilibrium will occur without a shift in technology, either in the form of an end-use substitute or in the form of a supply boost.

To account for the price mitigation effect of secondary supply, I analyze changes in market equilibrium in 2030. The technological shift of interest in this paper is the introduction of a battery recycling technology that can serve as a new source of supply. The cobalt extracted from the exhausted batteries can be sold back in the market, to make batteries or to serve the other end-uses and represents a source of secondary supply. Electric vehicles' batteries have the largest potential for recycling as they are easier to collect and transport to the recycling facilities. However, the number of electric vehicles on the road is still not very significant as only less than 3% of cars are electric (Bloomberg, 2021). Li-ion batteries used in mobile phones present a much bigger opportunity for recycling. Summed together, recovering cobalt from exhausted li-ion batteries can supply about 40,000 tons of cobalt in 2030. As shown in Figure 6, the introduction of recycling drastically decreases the 2030 cobalt price.

Solving for market equilibrium, the new price after the introduction of recycling is USD 344,996 per ton of cobalt, up 335% from the 2018 price equilibrium. The new equilibrium quantity is 354,300 tons produced, up 150% annually from 2018 to 2030. This quantity falls in the range predicted by Olivetti et al. (2020) which forecasted a supply between 320,000 and 460,000 tons.

Figure 6: estimated adjusted global cobalt market equilibrium in 2030 post-recycling



Compared to the non-recycling scenario, the equilibrium post-recycling makes cobalt more competitive for the battery market. The difference between the global price in 2030 with and without recycling is 511,213 USD/ton, more than a 60% decrease from the 2030 equilibrium without recycling. The magnitude of such difference can explain the importance of the introduction of recycling policies to make batteries more sustainable. The limitations of this forecast analysis lay in the estimations of coefficients as well as in the formulation of the assumptions. In particular, the EU Green Deal goals of 100% collection for EV batteries and 70% collection for smartphone batteries might not be achieved. For this reason, a sensitivity analysis was performed around battery collection targets to study how different rates might affect cobalt price and quantity (Table 4, 5).

Table 6: Sensitivity table for Cobalt equilibrium Quantity

Quantity	**Electric Vehicles battery Collection Rate (%)**				
Smartphones Battery Collection Rate (%)		**30.00%**	**50.00%**	**80.00%**	**100.00%**
	10.00%	302,601	309,664	320,259	327,322
	20.00%	307,097	314,161	324,755	331,819
	50.00%	320,586	327,650	338,244	345,308
	70.00%	329,579	336,642	347,237	354,300
	100.00%	343,068	350,131	360,726	367,789

Table 7: Sensitivity table for Cobalt equilibrium Price

Price	**Electric Vehicles battery Collection Rate (%)**				
Smartphones Battery Collection Rate (%)		**30.00%**	**50.00%**	**80.00%**	**100.00%**
	10.00%	685,328	619,859	535,446	486,955
	20.00%	642,723	582,170	503,927	458,886
	50.00%	533,072	484,842	422,141	385,834
	70.00%	472,611	430,954	376,591	344,996
	100.00%	396,915	363,232	319,040	293,224

Overall, the model proves the necessity of the introduction of a supply shock driver to balance the increasing demand for cobalt driven by the sharp increase in EV sales. The limitations of this forecast lay in the selection of the instruments. In particular, the demand might be overestimated as battery manufacturers in the long term might shift away from cobalt and switch to different cathode chemistry. My model does not account for substitution effects. Furthermore, supply might be under-identified under this model as DRC copper mining might not account for all the future cobalt production. Indeed, primary cobalt mining could origin from new countries attracted by the lucrative market. Finally, the mined cobalt ore quantity was used for identifying the demand curve, assuming market clearance's condition. In reality, the market could face an oversupply, or market unbalance, that would leave an additional stock of cobalt available for the next year.

VII. Conclusion

In this study, I used instrumental variables and simultaneous equations to identify the price elasticities of cobalt supply and demand assuming a perfectly competitive market. With yearly data spanning from 1981 to 2018, both the supply and demand curves were identified using the three-stage least square method. The instruments used were both strong and credible under the 3SLS estimation. Seven out of eight coefficient estimators were at the 0.1% confidence level. The Democratic Republic of Congo conflicts coefficient was significant at a 0.1% level. In agreement with the theory of perfect competition, my model identifies an upward sloping long-term supply curve and a downward sloping long-term demand curve. The price elasticity of cobalt supply is 0.13 and the price elasticity of cobalt demand -0.23 is, indicating inelasticity for both curves, with supply more price inelastic than demand. The results of the forecast analysis show that the price of cobalt could increase almost 1000% and the quantity supplied will reach 279,939 metric tons in 2030. However, the introduction of recycling as a new source of supply can decrease the price by 60% and boost supply by 23%, assuming an exhausted battery collection rate of 100% for EVs and 70% for smartphones. Sensitivity analysis around collection rates was performed to analyze less positive scenarios. These results show the benefit of the introduction of a closed-loop supply chain of cobalt, where the metal used in LIB can be recovered at the end of the battery life. The criticality of cobalt supply, strictly connected to the geopolitical conflict in the DRC, calls for the introduction of a supplemental source of production that can mitigate the supply risks. Recycling, as measured in this study, proves to be a cost-effective ally to meet the high projected demand for cobalt coming from an increasing GDP and a boom in EV sales in 2030.

There are few limitations associated with my research. First, I assumed both demand and supply functions are log functions with fixed coefficient and additive errors. In the future, different instrumental variables could be used to better identify supply and demand curves. Second, my assumption of perfect competition does not necessarily reflect the cobalt market that could be represented by a bilateral oligopoly model. A game theory model in future studies could capture the monopolistic nature of the market. For what concerns the limitations of my recycling simulations, a major shortcoming is the set-up of the curve independent from its marginal cost. It is likely that collecting and recycling batteries might be more costly with increasing quantities, or the opposite. Next studies should include a more specific parametrization of recycling supply to better capture its effects on the global cobalt market. Moreover, further attention should be paid on the type of cobalt recovered from exhausted batteries and whether its quality and price can compare to the cobalt ore sold in the market. This model is however a good starting point for evaluating the economic importance of recycling batteries and the data collected will be available under request for academic use.

Ultimately, this paper aims to give market credit to a circular economy of LIB. As the world aims to move towards a low-carbon economy it is essential to understand and mitigate the potential environmental, geopolitical, and social risks of powering the world through batteries. Replacing fossil fuels requires an exceptional sensitivity to the future of the metals supply chain to avoid running into the environmental, social, and governance issues that fossil fuels caused. The importance of introducing new players such as recyclers into the highly concentrated cobalt market entails a drastic remapping of power dynamics in the energy industry.

VIII. Work Cited:

Alves Dias P., Blagoeva D., Pavel C., Arvanitidis N., Cobalt: demand-supply balances in the transition to electric mobility, EUR 29381 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-94311-9, doi:10.2760/97710, JRC112285

Buchert et al. 2012 – Buchert, M., Manhart, A., Bleher, D. and Pingel, D. 2012. Recycling critical raw materials from waste electronic equipment. Darmstadt: Öko-Institut, 80 p

Cuddington, J. T., & Dagher, L. (2015). Estimating short and long-run demand elasticities: a primer with energy-sector applications. *The Energy Journal*, 36(1)

De Groot, H. L. F., Rademaekers, K., Smith, M., Svatikova, K., Widerberg, O., Obersteiner, M., ... & Lise, W. (2012). Mapping resource prices: the past and the future. *ECORYS: Rotterdam, The Netherlands*.

Friedman, L. (2020, March 24). A Trillion-Dollar Bet on Clean Energy. *The New York Times*

Goldberger, A. S. (1991). A course in econometrics. Harvard University Press.

Gupta, P., & Gupta, S. (1983). World demand for cobalt: An econometric study. *Resources Policy*, 9(4), 261-274.

Hotelling, H. (1931). The economics of exhaustible resources. The Journal of Political Economy, 39(2), 137-175.

Igogo, T. A., Sandor, D. L., Mayyas, A. T., & Engel-Cox, J. (2019). *Supply Chain of Raw Materials Used in the Manufacturing of Light-Duty Vehicle Lithium-Ion Batteries* (No. NREL/TP-6A20-73374). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Jacoby, M. (2019, July 14). C&EN. Retrieved March, 2021, from https://cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28

"Least Squares, Three-Stage ." International Encyclopedia of the Social Sciences. . Retrieved March 28, 2021 from Encyclopedia.com

Lydall, M. I., & Auchterlonie, A. (2011, July). The Democratic Republic of Congo and Zambia: a growing global 'hotspot'for copper-cobalt mineral investment and exploitation. In 6th Southern Africa Base Metals Conference, Phalaborwa (pp. 18-20).

McKinsey&Company (2018), Lithium and cobalt: a tale of two commodities.

Petavratzi, E., Gunn, G., & Kresse, C. (2020) *Cobalt: Commodity Report*, British Geological Survey

Reports, V. (2020, November 27). Lithium-ion battery market Size USD 129.3 billion by 2027 at A CAGR of 18.0%: Valuates Reports. Retrieved February 24, 2021, from https://www.prnewswire.com/news-releases/lithium-ion-battery-market-size-usd-129-3-billion-by-2027-at-a-cagr-of-18-0--valuates-reports-301181156.html

Renner, S., & Wellmer, F. W. (2019). Volatility drivers on the metal market and exposure of producing countries. *Mineral Economics,* 1-30.

The World Bank. *The growing role of minerals and metals for a low carbon future*. The World Bank; Jun. 2017. 117581.

Van den Brink, S., Kleijn, R., Sprecher, B., & Tukker, A. (2020). Identifying supply risks by mapping the cobalt supply chain. *Resources, Conservation and Recycling*, *156*, 104743.

Xinkai Fu, Danielle N. Beatty, Gabrielle G. Gaustad, Gerbrand Ceder, Richard Roth, Randolph E. Kirchain, Michele Bustamante, Callie Babbitt, and Elsa A. Olivetti
Environmental Science & Technology 2020 54 (5), 2985-2993

Zele, A. A. (2018). *Cobalt demand: past, present, and future* (Doctoral dissertation, Massachusetts Institute of Technology).

Zhao, Y., Gao, X., An, H., Xi, X., Sun, Q., & Jiang, M. (2020). *The effect of the mined cobalt trade dependence Network's structure on trade price.* Resources Policy, 65, 101589.

Zhu, Z. (2012). Identifying supply and demand elasticities of iron ore. Unpublished honor thesis, Duke University, North Carolina, USA

VIII. Appendix

Appendix 1- Calculation of Recycling Cost

Recycling cost: To calculate current cost for collection and recovery of cobalt for used batteries I used the EverBatt model developed by Argonne National Laboratory. I assumed that the recycled batteries are of NMC (111) type (they have the same ratio of nickel, manganese and cobalt), focused geography in the US and used default transportation data. The results were given for three different technologies (Hydro, Pyro, Direct). My model will use the cheapest alternative. Additionally I worked with the Nth cycle team to get data on the cost of their technology using the EverBatt model. This proved to be the cheapest option available in the market for recycling cobalt. The final results indicate a cost of recycling on a range from USD17,160 to 53,571 per ton of cobalt recovered. These numbers are well below market price of cobalt and drastically lower than the projected 2030 price of 344,996 USD/ton.

Appendix 2- Data Handling

The main challenges associated with collecting data on global cobalt are 1) usually cobalt market reports come at a premium cost and are not publicly available for academic use 2) publicly available reports are mainly in pdf format, not excel 3) different reports and sources present drastically different numbers for supply and demand 4) annual data does not fully capture the fluctuation of cobalt whose spot price varies greatly on a daily basis 5) The USGeological Survey reports only cobalt national consumption but presents data on international supply and mining.

To overcome such challenges each variable was carefully (and often manually) compiled into the database that will be made available for academic use under request (elena.cavallero@duke.com). Below, a more detailed explanation of the handling needed to compile the database:

- Cobalt Price: data for annual cobalt price was calculated as the average of the monthly cobalt ore price as reported by the International Monetary Fund Primary Commodity Prices. The IMF reports U.S. cathode spot price. The dataset spans from 1980 to 2021. After gaining access to the dataset, I averaged the price for every year from 1980 to 2018. The dataset is available in decade long format with production data disaggregated by country.
- Cobalt and Copper Production: the British Geological Survey retains data since 1970 on cobalt exports, imports and production. However, they only come in downloadable pdf covering 10-years and are disaggregated by production country. I merged the four spreadsheets and aggregate production data to get the toilet annual cobalt ore production data. For DRC copper production data, after aggregating the fours spreadsheet, I summed production figures for all countries representing the territory of Congo during the years (Congo, Zaire, Democratic Republic of Congo)
- DRC Conflicts: The Uppsala Conflict Data Program records violent conflicts since the 1970s. They have a specific database based on African countries' armed conflicts ranked by violence severity (1 or 2). I filtered the database for DRC and Zaire and manually reported a dummy variable of 1 for every year with at least one major armed conflict happening. A 0 was reported to indicate that no armed conflict happened that year in the DRC territory.

Appendix 2- 3SLS Variables Correlation

Matrix of correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) Cobalt Price	1.000						
(2) Cobalt Production	0.615	1.000					
(3) World mobile subscriptions	0.670	0.982	1.000				
(4) DRC Copper Production	0.255	0.730	0.707	1.000			
(5) World GDP	0.742	0.952	0.976	0.564	1.000		
(6) US Interest rate	-0.608	-0.748	-0.771	-0.197	-0.864	1.000	
(7) DRC conflicts	0.050	0.136	0.181	-0.034	0.257	-0.347	1.000