The purpose of this paper is to provide a supply and demand analysis with regard to cobalt. This work considers the future of cobalt mining. In order to achieve this objective, several aspects of the mineral are presented. On the one hand, the supply side is analyzed in depth. On the other hand, in terms of the demand side, I will examine the different end uses of cobalt. A linear regression allows us to forecast the future production of cobalt based on mining. In order to undertake such an analysis, the electric vehicle (EV) analysis of the International Energy Agency (IEA) is used. The results presented are based on two scenarios. The first one is the New Policies Scenario. The second one is the EV30@30 scenario. The results show that, in the future, cobalt production will increase. It will be partially caused by the likely increase in the EV sector. Then, the results obtained are discussed. There exist several papers which also forecast a growing cobalt supply. Finally, a section is dedicated to business ethics. It brings to light the role of companies in the responsible production of cobalt.
Geneva School of Economics and Management

Master of Science in commodity trading
Michael Tamvakis, Professor

Master thesis

Supply and demand analysis of cobalt

Supervised by Professor M. Tamvakis
Geneva Schools of Economics and Management

Gaëtan Mbengi

Geneva, 10 May 2019

Route de villars-vert 25
1752 Villars-sur-GLâne

gaetan.mbengi@etu.unige.ch
Abstract

The purpose of this paper is to provide a supply and demand analysis with regard to cobalt. This work considers the future of cobalt mining. In order to achieve this objective, several aspects of the mineral are presented.

On the one hand, the supply side is analyzed in depth. Indeed, the origins of cobalt, the meaning of the word “cobalt” and different types of minerals or deposits containing cobalt are discussed. In addition, I will consider the market situation and the different stakeholders involved in the industry. A section relating to the refining process carefully explains the operations. I will then discuss the cobalt recycling processes, given that these may be an important source of supply in the future.

On the other hand, in terms of the demand side, I will examine the different end uses of cobalt. The lithium-ion battery market, which represents a huge proportion of the end use of cobalt, is highlighted. Currently, there exists several kinds of battery and in future, other substitute products will emerge onto the market in place of cobalt. I will also discuss the use of this metal in superalloys. Then, two subsections are devoted to the catalysts and the hard metals respectively, which are also part of the end use of cobalt. Finally, the use of cobalt for its ability to color objects, and the utilization of this metal in magnets, are discussed.

A linear regression allows us to forecast the future production of cobalt based on mining. In order to undertake such an analysis, the electric vehicle (EV) analysis of the International Energy Agency (IEA) is used. Indeed, the data utilized are introduced. A section is dedicated to the Mobility Model (MoMo), which permits the prediction of the future global EV stock, as well as the analysis that results in estimates of the future electric vehicle sales. The results presented are based on two scenarios. The first one is the New Policies Scenario. The second one is the EV30@30 scenario. The future electric vehicle sales are utilized in order to permit the development of the linear regression. The results show that, in the future, cobalt production will increase. It will be partially caused by the likely increase in the EV sector. Then, the results obtained are discussed. There exist several papers which also forecast a growing cobalt supply.
Finally, a section is dedicated to business ethics. It brings to light the role of companies in the responsible production of cobalt.
# Table of contents

1. Introduction .................................................................................................................. 6
2. Supply ............................................................................................................................ 8
    2.1. Cobalt history ....................................................................................................... 8
    2.2. The mineral and the deposit types ...................................................................... 9
    2.3 The market ........................................................................................................... 12
    2.4 The refining process ............................................................................................ 17
    2.5 The recycling process .......................................................................................... 21
        2.5.1 The physical processes .............................................................................. 22
        2.5.2 The chemical processes ............................................................................ 23
        2.5.3 The commercial recycling operations ......................................................... 23
3. Demand .......................................................................................................................... 25
    3.1. The superalloys .................................................................................................... 25
    3.2 The batteries ......................................................................................................... 28
    3.3 The catalysts ......................................................................................................... 32
    3.4 The hard metals/hard facing ................................................................................ 32
    3.5 The pigment ......................................................................................................... 32
    3.6 The magnets ......................................................................................................... 32
4. The future cobalt supply .............................................................................................. 33
    4.1 The data ................................................................................................................ 33
    4.2 The Mobility Model ............................................................................................. 34
    4.3 The results ............................................................................................................ 34
        4.3.1 The Mobility Model results ...................................................................... 35
        4.3.2 Linear regression results .......................................................................... 36
5. Discussion ...................................................................................................................... 38
6. Business ethics .............................................................................................................. 39
    6.1 Child labor ............................................................................................................ 39
    6.2 Corporate social responsibility .......................................................................... 40
    6.3 Responsible production ....................................................................................... 42
7. Conclusion ..................................................................................................................... 46
8. List of references .......................................................................................................... 48
9. Recommended bibliography ......................................................................................... 49
10. Appendices .................................................................................................................. 53
# Table of Figures

**List of Figures**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Cobalt minerals</td>
<td>10</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Cobalt producers</td>
<td>13</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Historical prices graph</td>
<td>15</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Refining processes methods</td>
<td>19</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Process chain</td>
<td>21</td>
</tr>
<tr>
<td>Figure 6</td>
<td>End-uses of cobalt</td>
<td>26</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Critical metallic components</td>
<td>27</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Impact of cobalt price</td>
<td>28</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Cobalt demand</td>
<td>31</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Global EV stock</td>
<td>35</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Global mining production of cobalt</td>
<td>37</td>
</tr>
</tbody>
</table>
1. Introduction

In the next 20 years, the consumption of non-fossil fuels may be preferred to that of fossil fuels. Indeed, countries are going to make huge efforts to reduce their carbon emissions by the introduction of new legislation. The reduction of these harmful emissions will limit the extent of climate warming which causes climate disruption. Moreover, nowadays public opinion looks negatively at overconsumption, waste and pollution due to technology. The attractiveness of electric vehicles is part of this global context. The boom in the EV market, added to the demand generated by the electronic market, will probably lead to an increase in the use of lithium batteries. This would make cobalt extremely important throughout the world. In this paper, I will try to explore several aspects of cobalt.

The thesis is split into five parts. To begin with, the first part concerns the cobalt supply. In this part, I will deal with the history of cobalt, and of minerals and deposit types containing cobalt. In addition, I will discuss the market for cobalt and the numerous refining processes. Finally, I will present several recycling operations. The chemical and the physical processes will be highlighted.

The second part is dedicated to demand for cobalt. Indeed, the major end uses of cobalt are considered. There are subsections covering superalloys, lithium-ion batteries and catalysts. Also, I will discuss hard metals, hardfacing, pigments and magnets.

In the third part, I will discuss the future of cobalt mining production. In the first subsection, the data used by the International Energy Agency (IEA) will be introduced. Then, in the second subsection, I will discuss the Mobility Model, which is a model used by the IEA in order to, inter alia, predict future global electric vehicles sales and the future global electric vehicles stock. In the third subsection, I will show the IEA results. Then, from the predictions concerning the sales of electric vehicles, I will undertake a linear regression in order to obtain a forecast of the future global cobalt mining output.

In the fourth part, I will discuss the results. In addition, I will show the knock-on effect which may be caused by the forecasted cobalt mining output.
Finally, I will discuss business ethics. In this section, child labor issues, corporate social responsibility and responsible production will be introduced.

Ultimately, this work aims to answer the question: how much cobalt will be mined globally in 2020 and in 2030? Given that the Democratic Republic of the Congo (DRC) is the main supplier of cobalt and this country owns more than the half of the global reserves of cobalt, an increase in the production in the future may imply new challenges. It may reinforce a reliance on that country. The producers may face ethical issues in the mining operations or in terms of the acquisition of mining authorizations. Effectively, there exists several cases illustrating these issues. Meanwhile, other producers may develop either new ways to produce cobalt or substitute products. For instance, the blockchain technology is something that can be applied in this area to solve an ethical issue. Also, the production of mined cobalt in 2020 and in 2030 could be lower than the demand for cobalt, and thus reveal a supply shortage. This situation could cause a brutal hike in the price of cobalt. End-users such as Apple, Tesla and Samsung worry about this scenario. That is why these firms want to secure their supply. Finally, all these stakeholders will be linked in one way or another to the DRC.
2. Supply

In this section, I am going to focus on the supply side of cobalt. The history, the geological source and the geographical origin of this metal will be considered. I will also discuss the market, and the refining and the recycling processes.

2.1 Cobalt history

Cobalt is a chemical element, referred to as Co in the periodic table of elements. It has the atomic number 27. This means that cobalt has 27 protons and 27 electrons. The metal has 12 radioactive isotopes which do not appear naturally. The most famous isotope is cobalt-60, which has a half-life of 5.3 years. Cobalt is a ferromagnetic metal with a melting point of 1,495 °C and a boiling point of 2,927 °C. Therefore, cobalt has high thermal resistance. Among the three most common ferromagnetic metals - cobalt, nickel and iron - cobalt has the highest Curie point at 1388 Kelvin (K), about 1,114.85 °C. The Curie point is the temperature beyond which the magnetic properties of the metal are weakened. Cobalt-based alloys are both corrosion resistant and wear resistant. Moreover, cobalt conducts electricity. The metal has a slow reaction with mineral acids such as sulfuric acid. It also has a very slow one with moisture. Furthermore, it does not react with dry air.

Its name comes from the German word “kobold”. Kobold refers to legendary gnomes allegedly living in the mines of the Schneeberg Mountains, which are located in Germany. In the Schneeberg Mountains, cobalt was found in conjunction with silver and nickel. Silver and nickel were the metals of principal interest. When problems in the refining process of both metals were encountered, people blamed the Kobold. Later, people found out that cobalt was the element which led to problems in the refining process.

2.2 The mineral and the deposit types

About 30 main ores contain cobalt, while approximately 100 other ores contain at least a little quantity of cobalt. Therefore, in most cases, cobalt is extracted as a by-product or co-product. Given that cobalt shares several comparable chemical features with nickel, both ores are found in the same location. It is extracted as a by-product of nickel except in the African Copperbelt, where it is mostly extracted either
as a main product or as a by-product of copper. The mineral is also extracted as a main product in the Moroccan mine of Bou Azzer. In 2017, it was estimated that most of the cobalt was extracted as a by-product of copper.

It must be clarified that among the myriad of cobalt minerals, only some of them have a high enough concentration to allow profitable mining. These minerals have a quite varied chemical compound.

Normally, rock-forming ores do not include large quantities of cobalt. However, it can be found in high enough concentrations in spinel. Spinel is a mineral found in almost every color. It can form gems of several colors. It is not a well-known gem, although some gems can achieve very high prices. Bright red spinel, known as Ruby Spinel, is the most valuable spinel. In the past, there was no distinction between true rubies and Ruby Spinel, as they look similar and are found in the same localities. Nowadays, distinctions can be made through hardness and x-ray tests. It was found out that many famous old "Rubies" were, in fact, spinel. For example, the Black Prince's Ruby which is part of the royal crown of Great Britain was discovered to be a spinel.

Cobalt can also be found in olivine, which is a mineral classified in the silicate group. In most cases, olivine is used as a slag conditioner in metallurgical processes. Olivine with a high magnesium content is added to blast furnaces in order to eliminate dirt from steel and to form a slag.

Finally, it can be found in chloride located in lateritic and hydrothermal deposits. Hydrothermal deposits are found where ores are concentrated by the movement of warm fluids.

The most common categories of ores containing cobalt are oxides, sulfosalts, sulfides and arsenides. The major part of cobalt production comes from sulfide minerals, such as, for instance, pyrite or pyrrhotite. Figure 1 shows several minerals located in economic deposits.
Erythrite, also called red cobalt, is a pink/red ore. Its color is due to its cobalt content. Skutterudite is a mineral which has a color varying from gray to white. Given that Skutterudite holds arsenic, it needs to be managed carefully. Cobaltite is a quite rare mineral which also contains arsenic. Carrolite is a sulfide of cobalt, copper and nickel which is mainly found in the African Copperbelt.

It is important to note that more than half of the global cobalt production comes from the African Copperbelt. Linnaeite is an ore containing cobalt and this mineral is a sulfide. Asbolite is a mineral containing manganese oxide and cobalt oxide. To this list, Siegenite can be added.

On the sea floor, large quantities of cobalt are found. It is held inside manganese nodules and in cobalt-rich crusts. The cobalt content of these minerals may reach 2.5%. However, it is not economically viable to mine using the current technology and

Source: www.cobaltinstitute.org/ores-containing-cobalt.html
in the current situation. According to Mudd et al. (2013), cobalt with a high enough concentration to be economic can be found in seven different types of deposit:

1. Stratiform-sediment hosted deposits are formed by processes which convert sea water sulphates to sulfides and concentrated metallic material. In these deposits, sulfides containing cobalt and copper are mainly found. This type of deposit is responsible for about 50% of the global cobalt mine production. The average grade of the minerals varies between 0.2% and 1% according to Mudd et al. (2013). The deposit of Tenke Fungurume in the DRC belongs to this category. Pyrite-Big Hills in Australia is another relevant example.

2. Magmatic sulfide deposits are formed when an immiscible liquid sulfide is concentrated in magmas. This stage gathers and concentrates metallic elements such as cobalt. The fields of Norilsk in Russia and Sudbury in Canada are relevant instances. In these deposits, the cobalt concentration in the ores is at most 0.1% according Mudd et al. (2013).

3. Laterite deposits are formed because tropical weathering causes the breakdown of cobalt silicates and sulfides in magmatic rocks. The collapse makes them cobalt enriched. In terms of these deposits, Mudd et al. (2013) state that the grade of minerals varies between 0.1% and 1%. Koniambo Massif in New Caledonia is an example of a laterite deposit.

4. Magmatic-hydrothermal deposits contain magmatic stones. These stones are magnetite minerals, chalcopyrite minerals, and pyrite minerals holding cobalt. The deposits of Morgantown and Cornwall in the USA are pertinent instances.

5. Volcanogenic massive sulfide deposits are made by underwater-hydrothermal operations in old volcanic stones. These minerals are mainly pyrrhotite or pyrite. Deposits in the Finish region of Outokumpu and in Canada more precisely in Windy Craggy are relevant instances.

6. Replacement deposits are mined especially for cobalt. The cobalt found in the replacement deposits of the region of Gowganda in Canada has a concentration as high as ten percent. The mine of Bou-Azzer in Morocco contains a 1.2% cobalt concentration on average. Mudd et al. (2013) indicate that the concentration is usually approximately between 0.2% and 0.5%. The deposits in Burma are good instances.
7. Chemical precipitate deposits are bound to manganese and iron precipitation. These minerals are bound either near the ocean floor in hydrothermal systems, or pending weathering like in Mount Tabor, Australia.

2.3 The market

The Democratic Republic of the Congo (DRC) is the largest cobalt producer in the world. According to the U.S. Geological Survey (2018), in 2017 the country produced 73,000 tons (t), which represents about 60% of the global cobalt production. In 2018, the Congolese production was estimated at 90,000 t, in other words approximately 64% of the total cobalt production. Much of the cobalt production is mainly extracted as a by-product of copper. Also, it can be extracted as a by-product of nickel. Therefore, the supply is more responsive to the price of copper and the price of nickel than on the price of cobalt. Therefore, the supply is linked to the copper market and the nickel market. This limits the opportunities to answer rapidly to a sharp growth in cobalt demand. The other producing countries are very heterogeneous. DRC owns roughly half of the global reserve. Every Congolese deposit which produces cobalt is stratiform-sediment hosted. All of them are in the ancient province of Katanga.

In 2017, between 12 kilotons (kt) to 15 kt of cobalt were provided by recycling. Such cobalt usually comes from alloys. Currently, the recycling processes involving the recovery of cobalt from batteries are not well developed. It is difficult to recover cobalt in this way because the cobalt content of the batteries is very low. It is a concern for the industry. Investment is expected to be made in this activity given that the first generation of exhausted electric vehicle batteries will soon be available for recycling. These recycled batteries will represent a large volume. I will consider this subject in greater depth in Section 2.5 below.
In 2017, Glencore was the main production company with 27.4 kt of cobalt, which represents approximately 22% of the global supply. The last report with regard to Gecamines cobalt production states that the Congolese owned-state company produced 4.167 kt of cobalt in 2016. China Molybdenum’s cobalt production was 16.419 kt in 2017.

Cobalt is part of the category “minor metals”. It does not have an elevated level of transparency and liquidity in terms of pricing. In fact, cobalt contracts are illiquid. Indeed, there have only been an average of 354 contracts since early 2016. It is a small number compared with copper contracts. Copper has an average of 331,000 contracts. Given that the market is growing, cobalt transparency and liquidity is expected to grow over the years. Financial traders are starting to get into this market which will make the contracts more liquid.

The maturing phase of the cobalt market will play a huge role in the success of the battery component market for electric vehicles (EV). Regarding transparency, the cobalt price is not transparent because there are transactions that are deeply under the spot price at several periods. Moreover, the details of these transactions are not openly disclosed. This implies that the purchasers have to be fully aware of the market situation when undertaking a transaction.
The London Metal Exchange has been quoting cobalt since the 18th February 2010. On the 21th March 2018, the cobalt spot price reached a peak of 95,000 dollars/t. Given that the supply has been stable in recent years, it can be confirmed that the price variation was caused by an increase in demand. Indeed, the feeling that, in the short term, supply cannot match the level of the growing demand caused notably by the batteries market, pushed the price up to its peak. Investment is needed in order to increase the supply. That is why, the supply has increased slightly to match the demand. Also, the growth rate of the refined cobalt supply was forecast to increase. However, the refined quantity is lower than the global cobalt consumption. The growing cobalt consumption was led by the batteries sector and by the aerospace sector. Thus, in the short term, the global cobalt supply is expected to be limited.

Regarding the country’s production situation, the instability of the main cobalt supplier, DRC, does not encourage some much-needed investment in order to increase the cobalt supply. The political instability is brought to light by the delay of the Presidential and the legislative election from 2016 to 2018. The recent new Mine Code, which entered into effect in 2018, states that cobalt is a strategic mineral. Therefore, the taxes related to cobalt mining increased from 2% to 10%.

In addition, there are a few ownership disputes such as the one about the Tenke Fungurume ownership. China Molybdenum purchased the Tenke Fungurume mine. There were months of negotiation before Gecamines, the Congolese state-owned mining company, approved the purchase. Without this approval, the mining operations could not start. Furthermore, operational disputes like the one in the Kamoto mines may bring instability. Following the discovery of uranium content in the cobalt mined in the Kamoto mine, Glencore has stopped the extraction operations. However, the state-owned company, Gecamines, which on another note owns 25% of the joint-venture Kamoto Copper Company (KCC), founded with Glencore and holding the exploitation permit to extract minerals in the Kamoto mine, attempted to pursue extraction operations and has launched a survey in order to clarify the situation. These types of issues may give incentives to lower investment by increasing the uncertainty.

From the second quarter of 2018 until early 2019, we can see that the price has collapsed. Although the production of a few mines such as the Mutanda mine has
been reduced, the cobalt price has been decreasing. According to an article\textsuperscript{1} this is caused by large inventories

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{HISTORICAL_PRICES_GRAPH}
\caption{Historical prices graph}
\end{figure}

In the DRC, the mines are operated either industrially or artisanally. Recently, articles have brought to light two different strategies on the part of two Swiss trading companies concerning the mining operation.

On the one hand, Glencore advocates an industrial way to mine the ores excluding the purchase of the artisanal workers’ production. According to a declaration by a Glencore employee in the newspaper Le Temps\textsuperscript{2}, a lot of artisanal mines are illegal, they do not pay taxes, are unsecured, pollute, and hire children.

Although in the DRC the Mining Code and the Mining Regulations stipulate that the depth of shaft mining shall not exceed 30 meters, many tunnels are longer than the authorized limit. Indeed, “…in reality less than 10% of the miners have any


\textsuperscript{2} www.letemps.ch/economie/deux-geants-suisses-saffrontent-bataille-cobalt (17 November 2018)
knowledge of these regulations. Some miners dig without coordination and without any awareness of the last digging that could impact on the mine’s stability. Collapses due to erosion and wild mining can threaten houses.

Furthermore, some mines are not well ventilated, and dusty conditions are endured by the workers during the dry season. The work is harsh and there is a risk that the mine will collapse, given that the workers dig artisanally. The risk of collapse is greater during the rainy season. A complete report of the number of accidents is unavailable in the DRC. In view of all these elements, cobalt is only extracted by Glencore industrially. The company does not purchase or treat any cobalt which is mined by artisanal workers according to the article in the newspaper Le Temps mentioned above.

The mineral that is artisanally mined may obviously be linked using child labor in the production process. In the DRC, the use of child labor below the age of 15 years is formally prohibited. From the age of 15 years onwards, young miners are allowed to work with parental authorization and with the Labor Inspection approval. However, these kids are either allowed to light the tunnel or to work in salubrious place. About 28% of the workers in the Copperbelt, in other words between 19,000 and 30,000 workers are under 15 years of age. About 14%, in other words, between 9,000 and 15,000 miners are between 15 and 17 of age. Children are involved in digging, sorting and washing ores. The littlest kids are employed to dig in the small tunnels. Indeed, they can mine minerals in these narrow mining shafts with less difficulty than a grown-up person.

Artisanal mining may also lead to water pollution. Indeed, during the ore washing process, which occurs just after mining the ores, the workers usually use the water that people utilize for cooking, for drinking or for personal hygiene even though it is prohibited. In addition, the radioactive content of minerals may not only pollute the water. It also affects the workers digging the ores or operating near mines containing radioactive minerals. Moreover, the artisanal workers impact on the profitability of potential mining projects by digging in an anarchic way. Consequently, the value and the attractiveness of the mine are impacted.

---

3 Tsurukawa, Prakash, Manhart (2011)
On the other hand, Trafigura wants to frame and regularize the artisanal activity because artisanal workers are very important in the DRC.

In 1998, the artisanal exploitation of cobalt was officially authorized. It created employment and it decreased social tension. However, in 2006 the law changed, and artisanal mining was not permitted in many areas. Currently, the activity is regulated, with between 110,000 and 200,000 artisanal workers. Their cobalt production amounts to between 12,800 mt and 25,600 mt. That is why, in its main production site of Mutoshi, Trafigura has launched a pilot project. It has built huge electrified barriers around the mine. Every miner is checked at the entrance in order to ensure that they are not under 18 years of age. The company also ensures that the workers are not under the influence of alcohol. About 5,000 workers work in the mine. Roads have been built in order to avoid any accidents involving vehicles and workers. A local cooperative ensures that the workers are aware of the security rules. It also checks that every worker benefits from having adequate equipment such as boots and helmets. According to a declaration of OECD experts in the newspaper Le Temps¹, artisanal activity is a matter of survival for the population.

2.4 Refining process

In recent years, the supply of cobalt extracted from mines has been greater than the refined supply, which amounted to about 94 kt in 2016. The difference may come from the inventories of intermediate and final products. It may also be explained by the probable direct sales of unrefined cobalt to the end users.

Although being the most important cobalt end user, China is also the most important refining country. About 80% of its cobalt consumption is related to the manufacture of batteries. It refines more than half of the global cobalt production. Unsurprisingly, China is the most important supplier of refined cobalt to the USA. Approximately 90% of the cobalt imported into China, in the form of ores or in the form of more concentrated material, comes from the DRC.

Given that the refining process is mainly undertaken by Chinese companies, this situation gives Chinese industry important bargaining power over foreign buyers in the markets related to lithium-ion batteries. Indeed, in 2018, the Chinese firm GEM bought one third of Glencore’s cobalt production. This bargaining power may be used
to make sure that prices do not collapse, given that most of the refined cobalt is controlled by one player. Therefore, the future of cobalt will be bound to Chinese development.

With the exception of Chinese cobalt refineries, the largest refinery is Freeport Cobalt’s Kokkola in Finland which refines about 11 kt per year. Also, Glencore’s Nikkelverk refinery in Norway produces about 5 kt of refined cobalt. Four kt of refined cobalt is produced annually by Sumitomo’s Niihama refinery in Japan.

Depending on the cobalt ore compound, the refining process can be done in different ways. Figure 4 below shows the main methods and refining processes of the most common groups of cobalt ores. Only primary production methods are shown in this figure. Therefore, the recycling process is not represented. It would represent only 12 kt to 15 kt. Other refining methods that do not appear in the table may be used anyway such as, for example, bio leaching. However, these refining methods are not included because of the low production volumes. The refined cobalt is separated into two categories in Figure 4.

Cobalt class 1, also called metallurgical cobalt, appears in the figure. It contains more than 99% of cobalt and is mainly used to make superalloys, magnets and hard materials. Moreover, due to its high solubility, cobalt class 1 powder may be used to manufacture batteries. In the literature, there is not any information showing that the refining process of cobalt powder is different from the refining process of cobalt class 1 products in terms of inputs and environmental externalities.

In addition, the cobalt chemicals appears in the figure. It is used for catalysts, colors and the manufacturing of batteries. Schmidt et al. (2016) show that the cobalt found inside batteries is cobalt sulfate, produced through a chemical reaction of sulfuric acid and cobalt class 1.

As seen above in Figure 1, the group Arsenide includes the mineral Skutterudite. It must be specified that in the case of cobalt, Erythrite, which is part of the Arsenate group, is nothing other than an oxidation product of Arsenide group minerals. Therefore, the Arsenate group refining process is similar to the Arsenide group refining process shown in Figure 4. This category of cobalt is mainly mined in Morocco, and the pyrometallurgical process can be used. In this case, these minerals
are roasted in order to remove the arsenic content. In the hydrometallurgical process, the cobalt content can be obtained by leaching. In this way, cobalt is precipitated with hydrogen. The product has a cobalt content of more than 99%.

The cobalt ores, which contain nickel are separated into two categories. They represent about 31% of the total supply. One category is called sulfide and the other is called limonite. Firstly, the sulfide ores are mined and crushed. Then, chemicals reagents for the froth flotation process are used to transform the crushed minerals into a concentrated product. At this stage, the copper content is expelled. Then, a pyrometallurgical process is necessary. Indeed, either a flash furnace or an electric furnace is used just after the concentrated product has been roasted. After the conversion process, a matte is obtained. Finally, the last stage consists of leaching the matte with chloride, ammonium and sulfuric acid. Nickel is expelled by using reagents and the last impurities are extracted by hydrogen reduction and an electrowinning process. The final product contains more than 99% cobalt.

Figure 4: Refining process methods

Source: Schmidt, Buchert & Schebek (2016)

The hydrometallurgical process, combined with high pressured acid leach, can be used for limonite ores. The acid which is used is sulfuric acid. Precipitated sulfides and precipitated hydroxide are obtained in the subsequent process. Releaching and a solvent extraction process are then used. Finally, hydrogen reduction is used to
obtain a product that is almost 100% cobalt content. Electrowinning is used on the hydroxide in order to obtain this pure cobalt.

The Caron process, which is a totally different process can also be used to obtain a product, which contains between 25% and 78% cobalt. However, we will not go into further detail, given that the process demands high energy and it causes significant loss of production. Indeed, “…experts anticipate that production volumes produced by the Caron process will decline within the next few decades”\(^4\).

The copper-cobalt ores which are mainly mined in the DRC may be found in the form of sulfides, oxides, hydroxides and carbonates. They represent about 64% of the supply. The crushing process and the froth flotation process are used in the case of the cobalt ores. The product is roasted and leached with sulfuric acid. The copper is extracted by using a solvent. Finally, an almost pure cobalt product is obtained after the electrowinning operation.

After mining the ores, the same process is used on the copper-cobalt oxides. The final product contains between 25% and 78% cobalt. It is mainly used in catalysts, colors and battery manufacturing. As can be seen in Figure 4, powder coming from cobalt class 1 and from cobalt chemicals are used for batteries manufacturing.

\(^4\) Schmidt, Buchert, Schebek (2016)
Figure 5: Process chain

2.5 Recycling Process

To bury batteries at the end of their lifetime is not the most efficient way to get rid of the metals contained inside. There are components that may be dangerous for the soil. Nowadays, there exist rules formulated by the European authorities concerning the treatment of end-of-life vehicles. Given the growing number of EV on the market, and the willingness to care about the environment, it is a matter of time before the European authorities introduce a “system of return”5.

Currently, the European battery directive members are revising the regulations. The development of the recovery process will lead to a decrease in greenhouse gas emissions. Indeed, the process aims to use recovered metals in place of ore mining activities in the future production of batteries. The European battery directive is in the form of a convention, which consists of several regulations for the adhering countries.

5 Alves Dias et al (2018)
The objective is to ensure better recovery processes with regard to batteries. Furthermore, it aims to mitigate the environmental pollution for which distributors, third parties, producers and end users are all responsible. According to the European battery directive, pollution is caused by negligence, lack of regulations, or lack of information. This convention states that the recovery of dangerous materials from batteries is an obligation.

The recovery described processes hereafter have been attempted. Only a few of them have been commercially used. These recycling processes are mainly used in order to recover cobalt. The first stage of the process is to destroy the packaging, in order to access the chemical and reactive materials, generally in the cathode, in the anode or, at times, in the separators.

2.5.1 The physical processes

These processes incorporate all of the mechanical processes for the detachment of materials depending on several features such as conductivity, density and magnetism. A common mechano-chemical operation is a process that enables the recycling of cobalt on the case of lithium-cobalt-oxide (LCO) batteries. Dissolution operations which are used in a few recovery processes, need reagents in order to dissolve the adhesive materials.

Mechanical separation processes

A dry climate is appropriate for these types of operation because it mitigates the exposure of the battery to aqueous vapor. Also, it reduces the potential damage caused by short circuits. Such short circuits may cause more damage in the presence of oxygen. The mechanical operations consist of crushing, filtering, magnetic separation, fine crushing and classification in order to obtain a concentrated substance. This substance will be recycled thanks to additional operations. The two steps of filtering and crushing enable a successful separation of the metal from the trash. A magnetic separator may also be utilized. Mechanical separation done before the leaching process upgrades the efficiency of the recovery. One of the most important things in the process is to minimize cross contamination and penetration.
2.5.2 The chemical processes

**Acid Leaching**

Substances such as ferrous materials, which is split from the packaging in the first treatment stage, is leached by an acid solution. Many experimental results show that the efficiency of cobalt leaching is highest using hydrochloric acid.

**Solvent extraction**

To recover cobalt, many solvents such as phosphoric acid may be used. A hydrometallurgical plant, splitting metal by liquid–liquid extraction, may allow the recovery of metals from batteries. The liquid-liquid extraction is a separation process based on solubility. The method includes the use of sulfuric acid and a solvent such as phosphoric acid. In this way, a high recovery of recycled cobalt may be obtained at elevated purities.

2.5.3 The commercial recycling operations

Commercial processes are outlined in the following sections. These operations are mostly a mix of a few mechanical separation operations and a few chemical processes. The processes have two objectives. The first is to get rid of toxic materials contained in the batteries, and to treat it. Obviously, the second is to retrieve the targeted metals.

**Val'Eas closed-loop operation**

The purpose of the Val'Eas closed-loop operation is to deal with scraps and end-of-life batteries. The complete battery is put in a furnace. A high temperature is used to avoid any explosion. In this way, cobalt is recovered. The product is then transformed into a powder. Finally, a refinery can produce cobalt using this powder.

**Etoile–Rebatt process**

Etoile-Rebatt is a recovery operation. It is a mix of mechanical separation and disassembly, and thermal and electrochemical operations. For safety purposes, the lithium material is unloaded. The cathode, the anode, the separator and the
electrolyte are split. Then, black pastes which are bound to the cathode are treated. The pastes are plunged into a solution.

In the case of LCO batteries, the recovered lithium cobalt oxide is filtered, cleaned and dehydrated. With approximately 16 kg of black paste, 12 kg of lithium cobalt oxide may be retrieved.
3. Demand

In this section, I will discuss the demand side of cobalt. The total demand for cobalt will be shown. Finally, the end-uses of cobalt will be examined.

In the global context of green energy production and lower carbon emissions, cobalt plays an important role. Indeed, a radical change in our lifestyle in order to pollute less, will probably imply more cobalt consumption. According to Cobalt 27 (2018), in 2017, the cobalt demand reached 104,000 t. Of this 15,600 t - about 15% - was related to lithium-ion batteries for EV. 39,520 t, about 38%, was related to lithium-ion batteries for purposes other than EV such as smartphone, tablets or laptops. These other purposes may also be, for instance, for the production of photovoltaic (PV) batteries, energy storage systems (ESS) and constant voltage (CV) batteries. 48,880 t, about 47%, was needed for metallurgical and other purposes.

3.1 The superalloys

The end-use of cobalt may involve two categories of cobalt - chemical cobalt, including batteries, and metallurgical cobalt, including superalloys. Over the years, the major end-uses of cobalt have changed. In the 1980s, the main use of cobalt was related to the production of superalloys. During the postwar period, superalloy production accounted for about 30% of the total cobalt demand. Before World War II, superalloys containing cobalt were not massively used. These superalloys were strong alloys of cobalt and nickel, resistant to corrosion at high temperatures. Chromium-nickel-cobalt-iron alloys and cobalt-base alloys are relevant instances of alloys containing cobalt. The nickel-base superalloys can also contain between 0% to 22% cobalt. Nickel may be used up to a certain quantity as a substitute for cobalt in these alloys. It is needed in the production of aircraft engines, more precisely in gas turbines. Turbines can be used to generate electricity, to pump gas or to propel marine craft. The addition of cobalt to nickel improves the product’s characteristics at elevated temperatures. Nowadays, superalloys are also used in the aerospace sector.

In Figure 6, it is possible to see the shift in cobalt end-uses from 2006 up to 2020. The demand for cobalt for batteries represented 20% of the total cobalt demand in
In 2006, it had risen to 51%. It is the major change in the end-use of cobalt during this decade. It is forecast to reach 62% of the total cobalt demand by 2020.

**Figure 6: End-uses of cobalt demand**

Source: www.globalenergymetals.com/cobalt/cobalt-demand

### 3.2 The batteries

From a chemical point of view, there are special features that a commodity must have in order to be utilized as a cathode in a lithium-ion battery. First, it must contain reducible ion and oxidizable ion. For instance, the raw material must react with lithium in a reversible way. This calls for an intercalation-type reaction in which the host structure basically does not change when lithium is added. The commodity must have an elevated free energy of reaction with lithium and a high capacity. In addition, it may go up to 4 volts. Also, the material must be a good electricity conductor. That is why a metal is usually used. Finally, its cost and its toxicity must be low.

Lithium-ion batteries were marketed for the first time in 1991 by Sony Energitech. In 2017, batteries represented 53% of the global cobalt demand and 78% of the chemical cobalt demand subdivision. The batteries can be used in different areas. The first one is batteries for EVs, which accounted for 15% of the total cobalt demand in 2017. The second one incorporates all other batteries such as those inside smartphones or laptops. This represented 38% of the global cobalt consumption in
2017. According to Cobalt 27 Capital Corp.\textsuperscript{6}, which quotes a Darton Commodities report, an EV needs between 4 kg and 14 kg of cobalt. For instance, the Tesla Model S using a battery with 95 kWh, contains 14.9 kg of cobalt. However, the same car using a lower battery capacity, contains less cobalt. According to Benchmark Mineral Intelligence\textsuperscript{7}, the Tesla Model X contains about 7 kg on average, while the Tesla Model 3, which is more recent than either car mentioned above, contains on average, about 4.5 kg of cobalt. The three cars use NCA chemistries. However, the NCA batteries of 2019 are not the same as those of 2009 or 2016. Indeed, some substitute products have replaced some of the cobalt in the Tesla Model 3 and in the Tesla Model X. As shown in Figure 7, the cobalt content depends on the battery chemistry and on the battery capacity.

\textbf{Figure 7: Critical metallic components}

<table>
<thead>
<tr>
<th>kg/kWh</th>
<th>Li</th>
<th>Ni</th>
<th>Co</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCA</td>
<td>0.10</td>
<td>0.67</td>
<td>0.13</td>
<td>0.00</td>
</tr>
<tr>
<td>NMC 111</td>
<td>0.15</td>
<td>0.40</td>
<td>0.40</td>
<td>0.37</td>
</tr>
<tr>
<td>NMC 433</td>
<td>0.14</td>
<td>0.47</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>NMC 532</td>
<td>0.14</td>
<td>0.59</td>
<td>0.23</td>
<td>0.35</td>
</tr>
<tr>
<td>NMC 622</td>
<td>0.13</td>
<td>0.61</td>
<td>0.19</td>
<td>0.20</td>
</tr>
<tr>
<td>NMC 811</td>
<td>0.11</td>
<td>0.75</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>LFP</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: NCA refers to nickel cobalt aluminium oxide, NMC refers to nickel manganese cobalt oxide (numbers indicate the atomic share of each metal), LFP refers lithium iron phosphate oxide.

Source: IEA (2018)

In 2016, 73\% of EVs sold have batteries containing cobalt. The plug-in hybrid EV contains between approximately 1 kg and 4 kg of the metal. A laptop incorporates about 30 grams (g) to 50 g of the commodity. A tablet contains about 20 g to 50 g of cobalt. Finally, a smartphone may contain about 5 g to 20 g of cobalt.

\textsuperscript{6} www.cobalt27.com/cobalt/about (26 March 2019)

The quantity of cobalt used per battery depends on the cathode. The cathode is the part of the battery which collects the electrons when the battery is in operation. When the battery is loading the electrons go back from the cathode to the anode. The anode is generally made of graphite. Moreover, lithium is used as the charge bearer between the cathode and the anode. The costs of raw materials used in the cathode are increasing as part of the total battery cost. Azevedo et al. (2018) evaluated that materials used will represent about 10 percent of the cost of an EV battery pack in 2018. In 2010, it represented three percent of the cost. From 2016 onwards, the cathode accounted for approximately a quarter of a battery pack cost. That is why the choice of the materials used in the cathode is affected by possible cost savings.

Following the cobalt price peaks in 2018, several battery producers planned to reduce the overall amount of raw materials needed. Indeed, they try to use less and less cobalt in manufacturing the battery. For instance, Tesla, which used NCA batteries for its Model S, now build a better version for the Model 3 with less cobalt content than in an NMC 811 battery. Tesla also has the objective to reduce the bulk of cobalt contained in its future batteries. In Figure 8 below, we can see the impact of cobalt price variation on the price of the Tesla Model S and the BMW i3. If the price of cobalt sees a 100% increase, the manufacturer’s suggested retail price (MSRP) of the Tesla Model S will see a 2.2% increase, while the MSRP of BMW i3 will see a 4.1% increase.

Figure 8: Impact of cobalt price

Source: www.cobalt27.com
The use of cobalt in cathode manufacturing allows a short recharge time. The energy density of cobalt-containing batteries is elevated. Therefore, these batteries may store large amounts of energy in a tiny space. This permits the manufacturing of lightweight batteries and allows EVs to maximize their driving range. Cobalt also allows the manufacturer to maintain battery robustness and ensure a long lifetime. Indeed, thanks to the features of this metal, batteries may cross charge and discharge cycles for a long period. The main and most useful properties of cobalt are that it has hard-wearing and wear-resistant physical-chemical nature, caused by its compressed molecular composite structure. Cobalt permits low self-discharge and an elevated discharge voltage. The metal provides thermal steadiness. Firstly, the heat capacity of cobalt is high. Indeed, its melting-point is as high as 1495 degrees Celsius. Then, alloys can be made with cobalt. Cobalt offers robustness at elevated temperatures. Finally, the metal has an ability to keep ferromagnetic features at elevated temperatures.

As explained above, different forms of lithium-ion batteries exist with different cathode compositions. Among them there is the lithium-cobalt-oxide (LCO) battery which is an old model. It had elevated specific energy and stable capacities. That is why LCO was widely used in smartphones, digital cameras and laptops. The major inconvenience of LCO is the short lifespan and the low thermal stability, the last of which might cause thermal runaway and explosions. It also has small load capacities. In other words, frequent recharging is necessary.

Nickel-manganese-cobalt (NMC) batteries and nickel-cobalt-aluminum (NCA) batteries represent 68% of the EV battery market share.

“Most carmakers have chosen nickel-manganese-cobalt batteries (NMC). EV pioneer Tesla’s favored battery technology – nickel-cobalt-aluminum or NCA – already uses less than 3% cobalt”8. NCA may be used for EVs, grid storage, portable computers or e-bikes. It has a high energy density. In order to replace the costly cobalt in the LCO cathode, NCA lithium batteries were produced. Given that the features of nickel and cobalt are quite similar, more nickel was used in the battery at the expense of cobalt. NCA was the first competitive LCO product. Cobalt represents about nine percent of the battery composition.

---

Batteries containing NMC cathodes have a long lifespan and produce high power. It is used, for instance, in EVs, medical devices, grid storage or power tools. Several types of lithium batteries incorporating NMC cathode are produced. Currently, NMC 111 is a very popular cobalt-containing battery. This means that the battery contains an equal amount of the three metals. In 2017, if you only take into account CV, PV and ESS, NMC 111 accounted for about 30% of the batteries produced. Forecasts show that NMC 111 will be used less and less over the coming years. NMC 532/622 has a higher energy density. It is cheaper than NMC 111 because of its lower cobalt content. Without counting the EVs batteries, NMC 532/622 does not represent a large share of the total batteries. Its share is expected to grow in future years. The NMC 811 battery is the most advanced and the most recent NMC battery. It is supposed to present the best performance. It was firstly constructed for the EV industry. However, its low price and its better performance gave incentives to use this battery in other areas. It is forecast that it will account for about half the batteries used in the non-EV sector in 2030.

Batteries without any cobalt content are also produced such as, for example, ones using lithium ferro phosphate (LFP), lithium manganese oxide (LMO) or lithium titanate (LTO).

In Figure 9, the demand for cobalt by section is shown. Azevedo et al. (2018) indicate that the cobalt demand for batteries was 36 kt in 2017. The authors consider both a base scenario and an aggressive scenario. In the base scenario, 92 million internal combustion engine (ICE) vehicles, 3 million hybrid electric vehicles (HEV), 4 million plug-in hybrid EVs, and 6 million battery EVs are expected to be produced in 2025. In the aggressive scenario, 87 million internal combustion engine (ICE) vehicles, 3 million hybrid electric vehicles (HEV), 5 million plug-in hybrid EVs, 10 million battery EVs are expected to be produced in 2025. That is why, in 2025 the authors expect a demand of 117 kt for cobalt for batteries in the base scenario, and they expect a demand of 166 kt for cobalt for batteries in the aggressive scenario.
Chinese battery manufacturer Contemporary Amperex Technology Ltd (CATL) is the largest supplier of EVs batteries in the world, ahead of the Panasonic Corporation. Therefore, China will be able to supply about 66% of the total number of EV batteries in the coming years.

The rest is spread between several states, including Japan, the United States of America and South Korea. China is the leader in the old battery technologies. However, the Chinese government has modified his subsidy program in order to give incentives to the use of NMC chemistry instead of LFP. NMC batteries have a better technology than LFP batteries. NMC is more suitable for the most recent EVs currently in the market.

CATL wants to construct its first production plant in Germany. The company is a supplier of Honda, BMW, Nissan, Volkswagen and Toyota. The development of China in term of technologies is continually evolving. Given that the research and development efforts are growing, the development is supposed to advance more quickly.
3.3 The catalysts

An interesting feature of cobalt in catalyst production is its protection from oxidation. Cobalt is used in the production of recording tape, food packaging and polyester fibres. Generally, the catalysts mix manganese and cobalt.

The metal is also used as a catalyst for hydro-processing. This process is important for oil refineries in order to lower the quantity of sulphur in fuels. Also, cobalt catalyst is used in the generation of hydrogen.

3.4 The hard metals / hard facing

Cobalt is used as an alloy in the manufacture of prosthetic parts and dental components. High levels of hardness, corrosion resistance and wear resistance are features needed for these objects. That is why cobalt alloy is needed. For example, hard-facing products like wire and electrodes need this alloy. Cobalt alloy is also used in the automotive industry and in oil drilling.

3.5 The pigments

Cobalt has been used in the production of colors and in ceramics for centuries. Materials containing cobalt have the ability to give color. This represented five percent of the global cobalt demand in 2017.

3.6 The magnets

Before a regional conflict in the DRC in 1978, magnets were mainly made of cobalt. After this incident, the cobalt price went up and this incentivised magnet producers to use substitute products. Therefore, magnets have contained increasingly less cobalt over the years. It is used in generators. These products represented three percent of the global cobalt demand in 2017.
4. The future cobalt supply

In the section below, I will discuss the forecast for the global EV stock as made by the International Energy Agency (IEA). Thanks to this global EV stock and to the global EV sales, I am able to forecast the global mining output of cobalt in the future. The origins of the data will be examined. The models used will be introduced. Finally, the results will be presented.

4.1 Data

First of all, in the global EV outlook for 2018 made by the IEA, the database used by the Mobility Model (MoMo) comes from 27 regions and countries assembled into four regional groups which are part of the OECD, together with 11 countries which are not part of the OECD. The data for the period 1975-2014 is gathered from a large variety of public and proprietary data sources. For some countries, the data for the period 1990-2014 is used. National data are mainly collected from national and international public institutions such as the World Bank, Eurostat or the Asian Development Bank. The data also comes from national authorities such as energy and transport department, or statistical entities. It is also provided by associations and NGOs like the Korea Automobile Manufacturers Association, the Japan Automobile Manufacturers Association or the National Association of Automobile Manufacturers of South Africa. Public study entities such as national laboratories or universities are used. The International Council on Clean Transportation and other private research entities may provide pertinent data. Private business and advisory organizations such as Segment Y, IHS Automotive/Polk, major automobile market studies and analysis entities, as well as the biggest energy companies and car makers, are used during the data gathering process.

The data from these different sources on vehicles in each of the 27 regions and countries is amassed and combined to provide an estimation of the total emissions, of the total energy consumption and of other pertinent energy metrics with regard to the regions and countries’ points of view.
4.2 The Mobility Model

The MoMo is a simulation model. It is also a technical and economic database spreadsheet that allows thorough forecasts of vehicle activity, transport activity, well-to-wheel greenhouse gases, energy demand and pollutant emissions depending on policy scenarios till 2060. The simulation model is made for a five-year time duration in order to make scenarios built on back casting and “what-if” evaluation. To facilitate the execution and the manipulation of the design process, MoMo is divided in modules which may be elaborated and refined separately.

A cost analysis and information on technology availability is needed. For the cost analysis, information on the policy environment and on technological costs are required. This allows us to apply it to a choice of models such as a nested logit or other approaches, enabling us to prioritize one technology option over another. The same model can be filtered based on the technology availability. Then, a comparison of the results is carried out. It shows the objectives that different companies and countries want to achieve. The more granularity there is in terms of users, in particular mileages, the more complex the study will be in terms of detail and model disaggregation. However, other parameters matter such as, for example, income levels and the vehicle segment under consideration.

4.3 Results

The following paragraph shows the results of two scenarios. The results are given without considering two and three-wheelers.

The New Policies Scenario (NPS) is the main scenario of the IEA study. This scenario integers the measures and the policies already put in place by governments. It also integers the probable effects of the policies expressed in official plans or targets.

The EV30@30 scenario is the follow-up of the Electric Vehicle Initiative, which targeted the accelerated use of EVs throughout the world. In this scenario, the objective is to achieve 30% of the market share in the form of EVs for the truck sector globally, in the bus sector, and in the light commercial vehicles sector. If the carbon
intensity of power generation falls to 50% by 2030, the EV30@30 scenario will also meet Paris Agreement goal.

4.3.1 Mobility Model results

The NPS presents a global stock of 13 million EVs by 2020. In comparison, the global stock of EVs was about 3.7 million in 2017. By 2030, the global stock will reach 130 million EVs. In 2020, the number of EVs sold would be about 4 million. The level of sales was 1.4 million in 2017. There would be sales of 21.5 million EVs by 2030. This corresponds to an average sales increase of 24% per annum during the projection.

The EV30@30 scenario presents a global stock of 228 million electric vehicles in 2030. It represents about 100 million more EVs than in the NPS. Approximately 38 million EVs will be sold in 2030.

Figure 10: Global EV stock

The outlook for EVs stock growth would first lead to an increase in EV battery production. Battery capacities are also expected to increase. It will lead to a battery capacity of 70 kilo-watt hours (kWh) instead of the current average capacity for light commercial vehicles of 20 kWh in China and 60 kWh in the USA. Moreover, it will lead to the construction of new facilities for EV battery manufacturing. The growing demand for batteries with higher capacity will probably have important implications on the cost of batteries. In addition, learning-by-doing will impact the costs. The demand
for batteries with a higher capacity will also have big implications on the demand for metals such as cobalt.

An increase in EV demand will lead to an increase in the demand for metallic components. The risks concerning the supply of metals used in battery manufacturing, such as cobalt, exists. Given that most of the cobalt refining capacity is in China, the risk becomes greater.

The results of both scenarios show that the market for EVs will increase. The lifetime of EV batteries, approximately ten years, combined with the rapid growth in demand for battery capacity, means that virtually all the material demand for higher battery capacity will have to be supplied by mining, at least until 2030.

4.3.2 Linear regression results

The database that I used in order forecast the global cobalt mining production, comes from several versions of the Mineral Commodity Summaries. This paper is published by the U.S Geological Survey. The Global Electric Vehicle Outlook 2018 produced by the International Energy Agency was also used for the global historical data. Regarding the EV sales for 2018, I used a specialized website\(^9\) to find the necessary data. This data is incorporated in an Excel spreadsheet.

The model used in order to make this forecast is linear regression. This allows me to forecast a value by using existing values. The forecast value is a value \(y\) predicted thanks to a given value \(x\). In our case, \(y\) is the global mining production of cobalt and \(x\) is the EV sales. So, I put in one column the EV sales for the period 2005-2018 and I add the estimated value for 2020 and 2030 under the NPS and EV30@30 scenarios. I computed the mean and the standard deviation of the EV sales for the period 2005-2018. The mean is 374.21 and the standard deviation is 584.12. In the next column, I set the global mining production of cobalt for the period 2005-2018 and I also computed its mean and its standard deviation. The mean is 98.98 and the standard deviation is 23.80. The correlation of both variables is 0.74. This is a strong correlation. The coefficient of determination which measures the goodness of fit of the model is 0.55. This value is worthwhile. The covariance is 10,322.39. Thanks to these values, I found the equation of the regression line which is as follows:

Then, in another column, I set our predicted global mining production of cobalt for the period 2007-2018 and for 2020 and 2030 under the NPS and under the EV30@30 scenarios.

In a column entitled “error”, I set the difference in percentage between our forecast values and the historical mining production of cobalt for the period 2007-2018. The average of the difference in percentage is computed in the form of a column error average. I used this error average to adjust our forecast value. For example, in 2020 under the NPS, sales of 4 million EVs are expected, and our predicted mining production of cobalt is 208.67 kt. Then, I adjust the value thanks to the error average, and I find 158.20 kt.

In Figure 11, we can see that in 2020, NPS expects 158.20 kt of cobalt mining production, as the EV sales estimated by the IEA is 4 million. In comparison, the EV sales for the year 2017 was only 1.15 million. Given that in NPS the EV sales for the year 2030 is estimated at 21.5 million, NPS forecast 559.59 kt of cobalt mining output. Sales of about 38 million of EVs are expected by the IEA for the year 2030 in the EV30@30 scenario. So, in 2030, a cobalt mining production of 938.05 kt is expected in the EV30@30 scenario.

Figure 11: Cobalt mining production

Source: Appendix 1
5. Discussion

In this section, I will discuss the results and their knock-on effect.

In its report\textsuperscript{10}, the U.S. Geological Survey forecast a cobalt mining production of 140 kt in 2018. According to JRC Science for a policy report for the European Commission (2018), in 2020 depending on several scenarios, the cobalt demand should vary between 123 kt and 171 kt. The same report forecasts a global cobalt demand in 2030 varying between 241 kt and 534 kt. Our results for 2020 and 2030 match these predictions.

So, there is no doubt that, in the coming years, the growing demand for cobalt will imply a growing cobalt supply in response. Therefore, investment in production are needed to avoid the risk of a supply bottleneck. The first issue caused by the need for a growth in cobalt production is related to the origin of the production. Indeed, DRC will certainly remain the most important producer and will increase its cobalt production. However, the Congolese artisanal miners will also produce a part of the cobalt needed. Indeed, according to Glencore CEO, “…there were no new major cobalt-producing mines set to come into production after 2020”\textsuperscript{11}. In fact, the biggest mining extension plan is the one made by Kamoto Copper Company (KCC). 25% of KCC is owned by Gecamines and the rest is owned by Katanga Mining, which is affiliated with Glencore. The extension may increase the cobalt supply by an additional 30 kt per year by the end of 2019. The Metalkol Roan Taillings Reclamation project based in Kolwezi, in the DRC, is another big extension. The program is led by the Eurasian Resources Group. It may provide an additional cobalt supply of 14 kt per year in 2020. Except for the projects in the DRC, the biggest extension is in Zambia. The Zambian Mopani Mine may provide an additional cobalt quantity of about 3 kt per year.

\textsuperscript{11} www.google.com/amp/s/amp.ft.com/content/54e6165a-34f3-11e9-bd3a-8b2a211d90d5 (5 February 2019)
6. Business ethics

In the following section, I will discuss the issue of child labor in the mining of cobalt. Then, concept of corporate social responsibility will be considered. Finally, several ways of producing cobalt more responsibly will be highlighted.

6.1 Child labor

Given that there are not any new cobalt mining projects, demand may be greater than supply in the medium term. That is why the growing cobalt demand could be in part satisfied by the Congolese artisanal miners who adapt their production depending on the price of cobalt. The risk is that the situation gives incentive to the use of more child labor.

Child labor does not comply with Human Rights and it may affect the image of firms. This also represents a legal and economic risk for the companies concerned and for the investors. Nowadays, the general attention of the media and of consumers is higher than in the past. Transparency and sustainability have become increasingly important. Child labor is a consistent issue. Indeed, the children represent the future of their countries. They are often forced into exploitative labor due to household debt or other financial factors, resulting in continuous poverty. Poverty is the most important cause of the use of child labor in the mining communities of the Copperbelt. The frequently-reported reason for using child labor is to increase family income. The families in the Copperbelt are significantly larger, poorer, and less educated than the average in the DRC. The closer they live to the mines, the more likely that they will have an adult that works in the industry. Miners living in this zone receive a relatively small share of the price paid for their downstream output.

International purchasers can expect firms to have severe policies with regard to the use of child labor, maybe more severe than national laws and international standards. International purchasers and brands want to meet international labor standards and to avoid bad press and the potential damage to their corporate identity and the value of their shares.

In order to avoid scandals involving child labor and to monitor every step of the cobalt mining process, some companies are developing blockchain technology. In January
2019, IBM, Ford, the South Korean firm LG Chem, and the Chinese company Huayou Cobalt announced that they have introduced a project to track cobalt supply from the DRC. IBM has experience in this area. The company has collaborated with Carrefour and Walmart in order to track food supply chains. The pilot project should start around June 2019. When leaving the Huayou mine, the commodity will be put in safe bags. Then, it will enter into a blockchain and tracked from the mine. It will go through the LG Chem smelter and finally will end at a Ford plant. Each participant will have to make sure that everybody has met OECD standards. The collected data will allow for complete transparency and traceability. Blockchain will also allow a real time view to the participants. The final purpose of this pilot project is to make this system accepted by more companies.

In the long term, the EVs share in the global vehicle fleet will increase. So, another way for carmakers or smartphone producers to avoid the child labor issue is to invest directly in the mines. Samsung and Apple have been in talks to buy cobalt directly from the miners on a multiyear basis. At the same time, it will allow these companies to reduce supply risks. However, these companies are not mining firms, and several new issues may appear. Given that the EVs will represent an increasingly bigger source of revenue for them, this option remains relevant.

Some car manufacturers will try to use less and less cobalt in their products. They will develop an interest in a commodity having quite similar features such as nickel. On the one hand, the dependency on cobalt will be switched to a nickel dependency which will involve more volatility and higher prices. On the other hand, the performance of the batteries could be badly affected by using less cobalt.

6.2 Corporate social responsibility

Nowadays, companies must take into account several challenges relating to their way of doing business. They must consider a societal point of view, an environmental point of view and an ethical point of view. Moreover, if the firm is listed on a stock exchange, the investors, the NGOs and every other stakeholders will pressure the firm to consider a code of ethics and law enforcement. The listed companies must publish information. So, currently a corporate social responsibility strategy is required
for each company. If a company fails to publish such a strategy, it could face tremendous issues.

Although since 2007 Glencore has been investing $6.5 billion US in the DRC, the company has faced water pollution and air pollution issues. When these issues were reported publicly, the corporate image was impacted. In such a situation, immediate reactions are expected. That is why the Swiss company compensated the people adversely affected by the water pollution, and it released a statement explaining that it supports transparency, local firms, infrastructure development and health.

However, sometimes the damage associated with alleged misbehaviours may be financial. Indeed, on the 3rd July 2018, Glencore announced that the federal Department of Justice of the United States was investigating allegedly corrupt activities in Nigeria, in Venezuela and in the DRC. Immediately, the share value dropped by 10%.

Also, the commodity trading company may be affected by a civil conflict. Indeed, through his work, Ross (2004) brings to light the causal link between commodity trading and civil wars. The author based his work on a sample of 13 civil wars that occurred between 1990 and 2000 and that caused more than 1,000 deaths. Among the 13 civil conflicts included in the sample, we find the civil war of 1996 in the DRC and the civil war of 1997-1999 in the DRC. Ross shows that commodity trading impacts the onset, the duration and the intensity of a civil conflict. He uses the relevant cases of the sample in order to prove it.

With regard to the DRC, the author explains that in the case of the Congolese civil conflict which occurred in 1997-1999, the existence of raw materials like copper, coltan, cobalt, gold or diamonds increased the probability of a civil conflict onset by inciting bordering countries to support rebels. Indeed, the bordering countries wanted to benefit from the resources to finance the war effort.

This civil conflict also supports the hypothesis that commodity trading affects the duration of the conflict because, first, the looting of the commodities by the rebels lengthen the duration of the war. In this way, the rebel movement is strengthened, and is able to resist the government. Then, when the profits of war are greater than the profits of the peace, the duration of the conflict is greater. Indeed, the profit that
the rebel movement, the bordering countries and some people earned does not offer incentives to stop the war. In our example, a peace agreement was reached in 1999. However, the Congolese civil conflict ended in 2002. The duration of the conflict is also impacted when either the government or the rebels sell the authorisations for a future exploitation. During the DRC civil war of 1996, the chief of the rebel movement, Laurent-Désiré Kabila, reached an agreement for $885 US million for future mining with American Mining Fields, an American company active in cobalt, copper and zinc trading. It allowed Kabila to win the war more quickly and become President. Then, during the DRC civil war of 1997-1999, this same type of agreement lengthened the duration of the war. In this way, the rebel movement strengthened. However, it did not win the war.

The intensity of the civil war is impacted by the existence of commodities because the government and the rebels fight for the control of the resources. The greater the value of these resources, the more bitter the civil conflict is. The existence of commodities may also impact the intensity of the conflict by inciting both opponents to exploit the commodities together. Both ideas are observed in the civil war of 1997-1999 in the DRC.

6.3 Responsible production

The growing demand for cobalt may be in part satisfied by the use of recycled cobalt. According to Azevedo et al. (2018), this would account for 25 kt in 2025. The awareness of the economic and the environmental profit linked to the cobalt recycling process make the reasons for developing the cobalt supply coming from the recycling process more obvious. The advantages of recovering cobalt are increasingly important for every stakeholder.

Given that the cobalt reserves are concentrated in the DRC, the development of the secondary sources allows a bigger diversity of suppliers. Indeed, the concentration of the reserves in one country represents a supply risk. Moreover, the market situation may change. The multiple end-uses of cobalt place cobalt as a strategic mineral. The growing cobalt demand implies supply chain challenges in every industry using this metal.
The structure of cobalt is not affected by the recycling process. Indeed, this metal does not deteriorate. It does not change, and it may be recycled infinitely. Discarded metal is a permanent resource. Effectively, it may be melted several times and it always allows the production of new materials. In this context, cobalt can be considered a resource which may never be exhausted.

In addition, a large quantity of energy may be saved by using discarded metal. So, recovering cobalt allows producers to save the energy which would be used in the processes starting from mining through to refining and manufacturing.

From the labor market point of view, the recovering industry creates employment and improves the economic situation. The Canadian Association of Recycling Industries issued a survey claiming that the industry directly hires more than 34,000 individuals, and more than 85,000 individuals indirectly. Recovered materials decrease the costs of production. They also permit firms to be more competitive. The cobalt recycling sector is continuously looking for innovations.

Last, but not least, cobalt recovery is environmentally friendly. Less energy is used in the recycling processes. It decreases the emission of greenhouse gases. Also, the use of this commodity is maximized. Moreover, less metals end up in landfill sites.

When taking into account the human rights issues and that of political instability, some producers try to use other materials instead of cobalt. Innovations ending in a change to a different supply source would decrease the risk of short supply. Such innovations will take a few years to come into being because of cost and technological constraints. However, until this materializes, cobalt will remain a critical commodity.

Similarly to what happened in the oil industry when prices were above $100 US per barrel, high cobalt prices give an incentive to developing substitute products through innovation. Several types of batteries have been developed in order to enhance quality and to control the costs of production.

A lot of innovations involve the decrease in the quantity of cobalt used in the cathode by utilizing different metals. In this way, the new generation of NCA batteries and NMC batteries are expected to monopolize cathode manufacturing in the EV industry.
As mentioned in the sections above, NCA batteries and NMC batteries contain less cobalt than LCO batteries. However, the diminution of cobalt content may be compensated for by the growing quantity of batteries sold.

The research into larger energy density, lower charging times, and longer lifespan gave incentive to the development of new battery models. There exist many models such as hydrogen fuel cells, redox flow batteries, graphene supercapacitors, aluminum-graphite batteries, thin-film batteries, silicon-dominant anode materials and solid-state batteries. There are innovations that will not completely disrupt the lithium-ion battery market. For example, one system may allow automobiles to charge the battery directly using sunlight. Or, the highways can be powered in lieu of automobiles. Few of these inventions can completely replace batteries. However, a few of them are facing economic and technical issues, which do not allow immediate development and immediate use.

Investments create an overcapacity that may decrease the price of cobalt. Large investments in substitute products have been noted. For instance, graphene is a new material that scientists want to use in future EVs, and recently Samsung has claimed to have developed a lithium-ion battery which contains graphene. This battery has a 45% bigger capacity than current batteries and can be loaded five times more quickly.

The solid-state electrolyte is another form of chemistry which has attracted growing attention. In this type of battery, cobalt is not needed. It is promising and will enhance the global security of the battery. In addition, it will permit the use of a little film made of lithium as the anode. Thus, the volume and the weight of the battery will be lower.

The marketing of graphene technology and solid-state electrolytes can offer several opportunities for the next cathode chemistries. However, the current situation in the industry shows that, in the short term, these cathode technologies will not change the market situation. Therefore, these processes will not affect the demand for cobalt in the near future.

Fresh types of battery such as supercapacitors, zinc air and fuel cells are also important. These are supposed to be a key source of future energy. The barriers preventing the large-scale development of these batteries are the costs, the
weight/kwh, the volume and the security aspect. The promotion of these products in order to have a large enough target clientele is a key point because in this way, the products will not be restricted to a small market.
7. Conclusion

After showing the aspects of cobalt and the future mining of cobalt, it is obvious that, in the near future, cobalt demand and supply will increase. Lithium-ion batteries including cobalt will be increasingly widely used. The sector relating to batteries, which notably incorporates EVs and electronic devices, will represent the major cobalt end-use. This tendency is supported by the multiple new regulations and objectives of international authorities. The results show this clearly. Moreover, other works have resulted in the same conclusion.

The way of mining more cobalt is crucial. Indeed, the additional volume demanded may be satisfied in the short term by artisanal workers. In the context of an interconnected world and the freedom of information, the stakeholders of the cobalt industry pay very close attention to law enforcement including such aspects as Human Rights. Nowadays, nobody would accept that the cobalt ores used in electronic devices and in the EV industry, should be mined by children. Unfortunately, sometimes it may be the case that this continues to happen. That is why the stakeholders try to integrate new technologies into the mining process. The blockchain process may be one of these new technologies.

As shown in my research, there are other ways to avoid this issue. The companies selling the end products such as Apple or Samsung may invest directly in the mining industry in order to ensure that there is no child labor involvement. The companies may also decide not to work with cobalt anymore. Or, at least, the firms may attempt to reduce the cobalt content of their products drastically. For example, Tesla is developing batteries containing less cobalt. The carmaker may replace cobalt by nickel or other substances.

Also, there are projects in the development phase which use other materials to make a high-performing battery. Graphene is one of these promising materials which will allow manufacturers to get rid of cobalt in the batteries. Moreover, the solid-state battery, which is a new type of chemistry, does not require cobalt. However, it will take several years before such batteries can be commercialized because they are still in the development phase.
Finally, another way to respond to the growing demand for cobalt is the development of recycling processes. Indeed, it is the less polluting way and may reduce the supply of cobalt through mining. Therefore, on the one hand, it may contribute to the lower use of child labor. On the other hand, it may contribute to reducing the negative externalities of cobalt mining.

The limitations to this research are the data provided by the IEA. The expected EV sales are generally wrong. Thus, the results obtained by using this data remain estimations, and I need to get closer to the reality. However, the annual EV report of the IEA is one of the few which considers EV data on a global scale. Moreover, the data is open to the public in contrast to that of private reports. In addition, most EV carmakers do not disclose the amount of cobalt content in their cars. So, it is not possible to compute accurately the amount of global cobalt mining by multiplying the EV sales and the cobalt content.

The correlation between the copper, nickel and cobalt prices and output should be an interesting and complementary topic to develop. Indeed, there may exist a level of copper or nickel price which does not give incentives to mine cobalt, as copper and nickel are co-produced with cobalt. Also, the potential preference of nickel over cobalt in battery manufacturing and its expected impact should be worthwhile covering.
8. List of references


2 www.letemps.ch/economie/deux-geants-suisses-saffrontent-bataille-cobalt November 17th, 2018


6 www.cobalt27.com/cobalt/about March 26th, 2019


8 www.mining.com/ford-says-carmakers-may-need-invest-cobalt-mines-soon February 8th, 2019


11 www.google.com/amp/s/amp.ft.com/content/54e6165a-34f3-11e9-bd3a-8b2a211d90d5 February 5th, 2019
9. Recommended bibliography

Books, articles, working papers


IEA. 2016. Global EV Outlook 2016 Beyond one million electric cars.


Kosaraju, S. 2012. A review of the importance of recycling lithium-ion batteries for lithium, in view of impending electric vehicle industry. Chalmers University of
Techology, Department of Chemical and Biological Engineering Industrial Materials Recycling; SE-412 96 Göteborg, Sweden.


**Websites**

www.reuters.com/article/us-batteries-recycling-analysis/metal-recyclers-prepare-for-electric-car-revolution-idUSKBN1DH1DS Retrieved December 4th, 2018

www.cfr.org/backgrounder/cobalt-boom Retrieved November 17th, 2018


www.globemetal.com/5-key-benefits-of-recycling-cobalt Retrieved November 17th, 2018

51
10. Appendices

Table 1: Excel spreadsheet

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Year</td>
<td>Sales (in thousands)</td>
<td>Global mining production of cobalt (Kilo tons)</td>
<td>Error</td>
<td>Forecasts</td>
<td>Adjusted error average</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2005</td>
<td>1,89</td>
<td>65,2</td>
<td>-24,19%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2006</td>
<td>0,34</td>
<td>68,9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2007</td>
<td>0,47</td>
<td>71,5</td>
<td>4,07%</td>
<td>68,58968</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2008</td>
<td>2,48</td>
<td>76,3</td>
<td>16,79%</td>
<td>63,48913</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2009</td>
<td>2,13</td>
<td>72,3</td>
<td>1,01%</td>
<td>71,56381</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2010</td>
<td>7,49</td>
<td>89,5</td>
<td>11,21%</td>
<td>79,46894</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2011</td>
<td>47,24</td>
<td>109,5</td>
<td>-87,19%</td>
<td>204,0401</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2012</td>
<td>117,84</td>
<td>103,6</td>
<td>-68,86%</td>
<td>168,7759</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2013</td>
<td>202,8</td>
<td>110,2</td>
<td>-24,93%</td>
<td>137,4502</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2014</td>
<td>322,7</td>
<td>123,3</td>
<td>-34,85%</td>
<td>141,2583</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2015</td>
<td>540,72</td>
<td>126,2</td>
<td>-29,36%</td>
<td>163,7712</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2016</td>
<td>744,22</td>
<td>111,1</td>
<td>-44,30%</td>
<td>160,1768</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>2017</td>
<td>1148,7</td>
<td>120,5</td>
<td>-31,98%</td>
<td>158,3725</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>2018</td>
<td>2100</td>
<td>140,2</td>
<td>-26,20%</td>
<td>176,5824</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2020 NP5: 40000  208,6776  158,2036
2030 NP5: 21500  798,1151  559,5931
2030 EV@30: 38000  1237,304  938,0469

Table 2: Excel spreadsheet 2

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.89</td>
<td>65.2</td>
<td>-372,234286</td>
<td>-33,778571</td>
<td>12576,582</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.34</td>
<td>68.9</td>
<td>-373,874286</td>
<td>-30,078571</td>
<td>11245,604</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.47</td>
<td>71.5</td>
<td>-373,744286</td>
<td>-27,478571</td>
<td>10369,959</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2.46</td>
<td>76.3</td>
<td>-373,754286</td>
<td>-22,678571</td>
<td>8440,8561</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2.13</td>
<td>72.3</td>
<td>-372,084286</td>
<td>-26,678571</td>
<td>9926,5772</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7.49</td>
<td>89.5</td>
<td>-366,724286</td>
<td>-9,478571</td>
<td>3476,0223</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>47.24</td>
<td>109</td>
<td>-326,974286</td>
<td>10,0214286</td>
<td>-3276,749</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>117.84</td>
<td>103</td>
<td>-256,374286</td>
<td>4,0214286</td>
<td>-1050,991</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>202.8</td>
<td>110</td>
<td>-171,414286</td>
<td>11,0214286</td>
<td>-1889,23</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>322.7</td>
<td>123</td>
<td>-51,541825</td>
<td>24,0214286</td>
<td>-1257,447</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>540.72</td>
<td>126</td>
<td>165,505714</td>
<td>27,0214286</td>
<td>4999,2223</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>744.32</td>
<td>111</td>
<td>370,005714</td>
<td>12,0214286</td>
<td>4447,9973</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1148.7</td>
<td>120</td>
<td>774,485714</td>
<td>21,0214286</td>
<td>16280,796</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>2100</td>
<td>140</td>
<td>1725,785714</td>
<td>41,0214286</td>
<td>70794,195</td>
<td></td>
</tr>
</tbody>
</table>

mean: 374,214  98,9786  0  0  10322,393
standard dev: 584,117  28,8014
co-efficient (y,x): 0.74247
a: 0.03025
b: 87,6571
Coefficient of determination: 0.55126