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PROGRAMA DE DOCTORADO EN INGENIERÍA DE PRODUCCIÓN, MINERO-AMBIENTAL Y DE PROYECTOS

TESIS DOCTORAL

LA INVERSIÓN EN MINERÍA DE LITIO: ACELERANDO LA TRANSICIÓN HACIA EL TRANSPORTE SOSTENIBLE

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RESUMEN

El objetivo principal de esta tesis doctoral es la de realizar un análisis integral de la minería del litio a nivel mundial para, a continuación, aplicar los conocimientos adquiridos en el análisis del proyecto de litio Cínovec, en la República Checa, así como en el de recuperación del material procedente de una antigua escombrera de la zona.

Para lograr este objetivo principal, se acometió en primer lugar un estudio detallado del sector de la industria minera de litio, desarrollándose un análisis de los recursos y reservas globales de litio y su distribución por todo el mundo; de la oferta y la demanda así como los mayores productores y consumidores; de las distintas formas en que se comercializa, así como sus subproductos; así como de la evolución del precio del litio. También se describieron los distintos métodos de extracción y procesamiento de los depósitos, tanto en rocas, como en salmueras subterráneas o en arcillas.

En segundo lugar, se estudiaron cinco proyectos mineros de litio diseminados por todo el mundo y listos para su lanzamiento, a los efectos de determinar los órdenes de magnitud económicos de esta industria. Cada uno de los proyectos analizados representa un enfoque diferente para la minería de litio: el proyecto Whabouchi en Canadá, que combinará un método convencional de minería a cielo abierto y subterráneo; el proyecto Keliber en Finlandia, que utilizará minería a cielo abierto; el proyecto Cauchari-Olaroz en Argentina, que extrae litio de salmueras; el proyecto Sonora en México, que extraerá litio de arcillas; y, finalmente, el proyecto Pilgangoora en Australia, que producirá exclusivamente un concentrado de espodumena mediante minería a cielo abierto. El análisis detallado de estos proyectos permitió determinar distintas relaciones y valores para los parámetros de la minería de litio: leyes de corte, ratios de dilución y extracción, recuperación metalúrgica, inversión en capital, gastos operativos y resultados financieros tales como el Valor Actual Neto, la Tasa Interna de Rentabilidad y el Período de Recuperación.

En tercer y último lugar, esta tesis se centra en el desarrollo de un estudio de alcance para el proyecto de Cínovec, utilizando los órdenes de magnitud establecidos anteriormente. Este proyecto está siendo preparado desde 2012 por la empresa australiana European Metal Ltd. Esta empresa planea explotar el yacimiento mediante minería subterránea. No obstante, el estudio de alcance que se desarrolla en esta tesis se plantea mediante minería a cielo abierto, dentro del área donde existen resultados de exploración disponibles. Para este proyecto se calcularon los recursos minerales, se creó un modelo de bloques y el subsiguiente diseño de la corta óptima. A continuación se realizaron los cálculos financieros, seguidos de un análisis de sensibilidad e incertidumbre. Finaliza esta tercera parte con el análisis de viabilidad de una escombrera procedente de la antigua explotación minera en dicha zona.

Las conclusiones obtenidas permiten afirmar que este tipo de estudios facilitan a las empresas mineras la realización de estudios de alcance de una forma rápida, económica

y eficiente, acelerando por tanto esa tan ansiada transición hacia el transporte sostenible, dado que el litio es uno de los elementos fundamentales para la consecución de dicho logro.

ABSTRACT

The main objective of this doctoral thesis is to carry out a comprehensive analysis of lithium mining worldwide and then apply the knowledge acquired to the analysis of the Cínovec lithium project in the Czech Republic and the recovery of material from an old waste heap in the area.

First, a detailed study of the lithium mining industry sector was undertaken to achieve this primary objective: analysing the global lithium resources and reserves and their distribution worldwide; analysing the supply and demand and the major producers and consumers; assessing the different compositions in which lithium is marketed as well as its by-products, and analysing the evolution of the price of lithium. The various extraction methods and processing of deposits, whether in rocks, underground brines or clays, were also described.

Second, five lithium mining projects scattered around the world and ready for the launch were studied to determine the economic orders of magnitude of the industry. Each of the projects analysed represents a different approach to lithium mining: the Whabouchi project in Canada, which will combine a conventional open-pit and underground mining method; the Keliber project in Finland, which will use open-pit mining; the Cauchari-Olaroz project in Argentina, which extracts lithium from brines; the Sonora project in Mexico, which will extract lithium from clays; and finally, the Pilgangoora project in Australia, which will produce a spodumene concentrate exclusively through open-pit mining. Detailed analysis of these projects allowed us to determine different ratios and values for lithium mining parameters: cut-off grades, dilution and extraction ratios, metallurgical recovery, capital expenditure, operating expenses and financial results such as Net Present Value, Internal Rate of Return and Payback Period.

Third and finally, this thesis focuses on developing a scoping study for the Cínovec project, using the orders of magnitude set out above. This project is being prepared since 2012 by the Australian company European Metal Ltd. This company plans to exploit the deposit by underground mining. However, the scoping study developed in this thesis is proposed by open-pit mining within the area where exploration results are available. For this project, the mineral resources were calculated, a block model was created, and the subsequent design of the optimal cut-off was carried out. Financial calculations were then performed, followed by a sensitivity and uncertainty analysis. This third part ends with the feasibility analysis of a waste dump from the former mining operation in the area.

The conclusions obtained allow affirming that this type of study makes it easier for mining companies to carry out scoping studies quickly, economically and efficiently, thus accelerating the longed-for transition towards sustainable transport, given that lithium is one of the fundamental elements for achieving this goal.

PUBLICACIONES DERIVADAS DE LA TESIS DOCTORAL

Las publicaciones que presentan los resultados obtenidos con esta tesis son los siguientes artículos:

- Sterba J., Krzemień, A., Riesgo Fernández P., Escanciano García-Miranda C., Fidalgo Valverde G., (2019). **Lithium mining: Accelerating the transition to sustainable energy**. *Resources Policy 62*, 416–426. https://doi.org/https://doi.org/10.1016/j.resourpol.2017.05.004

  RESOURCES POLICY pertenece a la categoría de Environmental Studies del JCR. En 2019 tuvo un Impact Factor de 3,986, su Rango en la Categoría es 26 de 123 y su Cuartil es Q1.

- Sterba J., Krzemień, A., Fidalgo Valverde G., Diego Álvarez I., Castañón Fernández C., (2020). **Energy-sustainable industrialized growth in the Czech Republic: the Cínovec lithium mining project**. *Resources Policy 68*, October 2020, 101707. https://doi.org/10.1016/j.resourpol.2020.101707

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1 INTRODUCCIÓN

1.1 Lithium

Lithium was discovered in 1817 by a Swedish scientist, Johan August Arfwedson, but only quite recently and due to the structural change in global economy it turned important. Lithium is a soft silver-white metal that belongs to the Alkali group of chemical elements. It is lighter than water, about half of its density, so it can even float. However, lithium reacts violently with water. Pure lithium metal is extremely corrosive and requires special handling. Because it reacts with air and water, the metal is normally stored under oil or enclosed in an inert atmosphere. When lithium catches fire, the reaction with oxygen makes it difficult to extinguish the flames. Moreover, as it is rated within the Mohs scale of mineral hardness with 0.6 (up to 10), it can be easily cut with a knife.

Because of these properties it is obvious that lithium´s potential is limited in many aspects. What makes lithium so special is the fact that it has the highest electrochemical potential among all the metals. This property is mainly used in rechargeable batteries as they provide efficient energy storage together with a smooth delivery. Other interesting properties of Lithium and its chemical compounds are (Fox Davies Capital, 2013): an extremely high co-efficient of thermal expansion, fluxing and catalytic characteristics, and to act as a viscosity modifier in glass melts. That is why it finds use in other industries such as glass and ceramics, lubricants others. Lithium has also been used to treat bipolar disorder and other mental illnesses such as depression, schizophrenia, and eating disorders for over a century, Anemia, headaches, alcoholism, epilepsy, and diabetes are all treated with it. (Miller, 2018). Below indicated in **Table 1** are some of the important physical properties of the lithium metal.

Table 1. Properties of the lithium metal (Pappas, 2018).

Atomic symbol	Li
Atomic weight	6.941
Density	0.534 g/ cm^3
Phase at room temperature	Solid
Melting point	180.5 °C
Boiling point	1342 °C

Some reports when informing about lithium resources and reserves can quote content as per lithium (Li), lithium oxide (Li_2O), or lithium carbonate (Li_2CO_3). Lithium forms a several compounds that are described further in this thesis. Because there are so many different lithium compounds, production amounts are frequently represented as lithium carbonate equivalents (LCE). Lithium carbonate equivalent is a word used in the industry to describe Li2CO3 and is equivalent to it. LCE is used to offer data that is comparable to industry reports, and it is the total equivalent quantity of lithium carbonate, assuming the deposit's lithium content is converted to lithium carbonate. Conversion factors between selected lithium forms are expressed in **Table 2**.

Table 2. Lithium Conversion factors for differing lithium substances (Savannah Resources, 2020).

To convert from:	**to Li: x**	**to Li_2O: x**	**to Li_2CO_3: x**
Lithium Li (100 % Li)	1.000	2.153	5.323
Lithium oxide Li_2O (46.4 % Li)	0.464	1.000	2.473
Lithium carbonate Li_2CO_3 (18.8. % Li)	**0.188**	**0.404**	**1.000**
Lithium hydroxide monohydrate $LiOH.H_2O$ (16.5% Li)	0.165	0.356	0.880
Lithium chloride LiCl (16.3% Li)	0.163	0.356	0.871
Lithium bromide LiBr (8.0% Li)	0.080	0.172	0.425

1.1.1 Lithium compounds

There are several lithium compounds produced commercially today. Each one of them is used for different purposes and has different properties. When it comes to lithium production, not all lithium compounds are made equal. The final lithium products must meet specific requirements as they are used in different applications. The lithium industry distinguishes three basic types or qualities of lithium compounds: “Industrial grade” with purity of over 96% used for glass, fluxing agent and lubricant. The “Technical grade” with a purity around 99.5% suitable for ceramics, lubricants and batteries and the “Battery grade” with purity over 99.5% used especially for high end battery cathode materials. The most common lithium compounds are following (British Geological Survey, 2016).

- **Lithium carbonate (Li_2CO_3)**, is an inorganic chemical compound with a density of 2110 kilograms per cubic meter and a melting point of 723 degrees Celsius. It has a poor water solubility, which can be used to recover lithium from minerals and brines. The addition of sodium carbonate to lithium chloride in fluids, followed by washing with water to remove the sodium chloride that forms, produces lithium carbonate. Lithium carbonate is the most common precursor for the production of various lithium compounds and products. It comes in a variety of grades based on purity and particle size distribution for various applications.

- **Lithium hydroxide (LiOH),** is an inorganic compound which is available in its anhydrous form or as a monohydrate with the chemical formula of $LiOH\text{-}H_2O$. It is produced by a chemical reaction between lithium carbonate and calcium hydroxide. The anhydrous form has a density of 1460 kg per cubic meter and the monohydrate form has a density of 1510 kg per cubic meter. Both forms have a melting point of 462 °C.

- **Lithium chloride (LiCl),** the most prevalent lithium-bearing chemical encountered in brine operations is lithium chloride (LiCl). It's a white solid with a melting point of 605 °C and a density of 2068 kg per cubic meter. It is made from lithium carbonate that has been treated with hydrochloric acid. The most common chemical form of lithium metal is lithium chloride.

- **Lithium bromide (LiBr),** is created by treating lithium carbonate with hydrobromic acid. It's a white solid with a melting point of 552 °C and a density of 3464 kg per cubic meter. As a result, it attracts and holds water molecules, making it an excellent desiccant for air conditioning systems..

- **Lithium metal (Li),** is produced by electrolysis from a mixture of lithium chloride and potassium chloride.

However only two of them are most widely commercialized: lithium carbonate (Li_2CO_3), for either industrial or batteries applications, and lithium hydroxide (LiOH). Lithium carbonate in battery grade with (purity min. 99.5%) is key raw material for the production of lithium battery cathode and electrolyte. On the other hand, a lithium carbonate with industrial grade (purity of min. 99.0 %) is used mainly for lithium metallurgy special glass, ceramics, glaze, electronic products etc. Lithium hydroxide which is becoming more and more important for batteries manufacturing, being also commercialised in its monohydrate version ($LiOH.H_2O$). Both compounds are used to produce cathode material for lithium-ion batteries. Lithium hydroxide is more expensive, as it decomposes at a lower temperature and the process of cathode manufacturing is less time and energy consuming. Because of this, while battery-grade lithium carbonate demand has increased by 19.0% per year since 2010, battery-grade lithium hydroxide has increased by 38.9 % (Met-Chem, 2016).

1.1.2 Lithium demand

The age of electromobility, energy turnaround, ban on diesel driving, nuclear phase-out, climate change – these and many other terms used in our daily language have led to a true turn of events in recent years that hardly anyone thought possible 25 years ago: The leap from the age of fossil combustion and consumption as immediate as possible to the decentralisation of energy production, the corresponding need for on-site storage and, ultimately, to a true revolution in mobility. After more than 100 years of combustion engines, the next stage of development is being ignited, and it is called electromobility.

Several countries have already jumped on the electric mobility bandwagon in order to achieve the climate targets they have set themselves and have initiated measures that will further accelerate the process of turning away from the internal combustion engine and towards the electric motor and sustainable transportation at the same time. Norway and the Netherlands, for example, have decided to ban sales of vehicles with internal combustion engines from 2025. India and France want to achieve this by 2030, as do Germany and China, although no final decision has yet been taken. Great Britain wants to follow by 2040. These planned measures put the car manufacturers under pressure, so that they have already reacted and have set the following company objectives. These objectives are summarized in **Table 3**.

Table 3. Automotive Industry strategy for electrification (Swiss Resource Capital ag, 2019).

Company	Objectives	Year
BMW	15 to 25% of all vehicles produced are to be powered purely by electricity, which is equivalent to a total of around 300,000 to 600,000 vehicles.	2025
Chevrolet	After 30,000 electric vehicles sold in 2017, no concrete targets defined yet.	N/A
Chinese carmakers	At least 4.5 million electric vehicles on the roads	2020
Daimler	15 to 25% of all vehicles produced are to be powered purely by electricity, which will affect a total of about 300,000 to 600,000 vehicles	2025
Ford	At least 13 models are to be powered electrically, which is about 10 to 25% of the entire model range	2020
GM	Complete conversion to electromobility	N/A
Honda	Two thirds of all vehicle models are to run with an electric motor (3.3 million)	2030
Hyundai	At least 10% electric vehicle share (800,000 vehicles)	2025
Peugeot	80% conversion to electric drive	2023
Porsche	Conversion of 90% of the product range to electric drives	N/A
Renault/Nissan	1.5 million electric vehicles	2020
Tesla	1 million electric vehicles	2020
Toyota	100% conversion to electric drive	2050
Volvo	100% conversion to electric drive (500 000 vehicles)	2019
VW Group	20 to 25% of all vehicles produced are to be powered purely by electricity, which is equivalent to a total of around 2 to 3 million vehicles	2025

Altogether, the leading car manufacturers plan to produce at least 20 million electric vehicles per year from 2025 alone. From 2030, 25 million electrically powered vehicles per year are expected and from 2040 even 60 million vehicles per year.

It is expected that the main driving factor for lithium demand will primarily be the demand from the battery and accumulator industry in association with the automotive industry. But also, the energy storage sector will create an immense demand. In 2015, only one third of the lithium demand came from the battery sector; by 2025 it will probably reach 70 % (Swiss Resource capital ag, 2019).

A large quantity of lithium is required for the production or operation of lithium-ion batteries. Every smartphone, for example, contains between 5 and 7 grams of LCE (lithium carbonate equivalent). With a notebook or Tablet it is already 20 to 45 grams.

Electric tools such as cordless screwdrivers or electric saws require about 40 to 60 grams for their batteries. A 10 KWh storage unit for domestic use requires around 23 kilograms of LCE, while batteries for electric cars require between 40 and 80 kilograms. An energy store with 650 MWh capacity needs about 1.5 tons of LCE. With quantities in the billions (smartphone) or in the millions (notebook, tools, cars, e-bikes, etc.), several 100,000 tons of LCE demand per year quickly accumulate. As the demand is increasing sharply mining companies react with investments into the exploration and expansion of the lithium mines. For instance, a Tianqi Lithium, China's largest producer of the white metal, is considering an investment of an extra A$516 million ($382 million) to increase lithium production at its Greenbushes mine in Western Australia, the world's largest hard rock lithium operation, as demand for the key ingredient to build batteries that power electric picks up. However, it is always the price of the product that decides what comes next. (Jamasmie, 2018).

Most of the demand for lithium comes from Asia. China alone accounts for one third of the total demand, today. Experts estimate this will not change soon because China produces the most accumulators, batteries, glass, lubricants, air conditioning units and synthetic rubber by far. According to expectations China will have the strongest yearly increase in lithium demand of all important market participants during the coming 5 to 10 years due to an expected tripling of the quantity of rechargeable batteries. Additional important suppliers of lithium-ion batteries including South Korea and Japan will also guarantee a robust increase of the lithium demand.

Use of lithium nevertheless goes beyond the batteries. A several important industries consider lithium as a element of high importance. For instance, a Ceramic and glass industry in 2019 consumed about 18 % of total lithium, while consumption in the same year of lithium for purposes of battery manufacture reached 65 % of total consumption. Lithium oxide is utilized as a flux in the ceramic and glass industries because it lowers the melting point and viscosity of silica-based materials, conserving energy and lowering production costs. Because lithium has a low coefficient of thermal expansion, lithium-containing glass or ceramic glazes are more resistant to higher temperatures and allow items to tolerate temperature changes. Lithium glass is also more resistant to chemical assault and has better hardness and luster. When lithium is coupled with copper, blue glazes result, while when lithium is coupled with cobalt, pink glazes result.

Another industry where lithium compounds are used is a production of lubricant greases. A lubricant grease is a sort of lubricating fluid that has been thickened with a thickening agent to help the lubricant stay where it's needed. When lithium hydroxide is heated with a fatty substance, a lithium soap grease is formed, which is one of the most widely used lubricating greases due to its high performance and low cost.

Lithium bromide and lithium chloride are both significantly hygroscopic and therefore are used quite often in air treatment industry (air conditioning). They transform carbon dioxide to lithium carbonate and use it to extract it from confined spaces like submarines and spacecraft. This procedure also includes the use of lithium peroxide, which releases oxygen during the process.

Since it facilitates the flushing of other metals while also absorbing any impurities, metallurgical lithium is used as a flux in welding or soldering. In the production of specialized aircraft components, lithium is alloyed with aluminium, cadmium, copper, or manganese.

Butyllithium and other organolithium compounds are used in the manufacture of polymers and other chemical applications. Lithium compounds are typically used as reagents, catalysts, or initiators in these applications. Lithium compounds, such as lithium carbonate, are used in medicine as mood stabilizers and in the treatment of bipolar disorder. Lithium is also used for the psychiatric disorder and a range of non-psychiatric illnesses. In **Figure 1** a lithium consumption by end use in 2019 is presented.

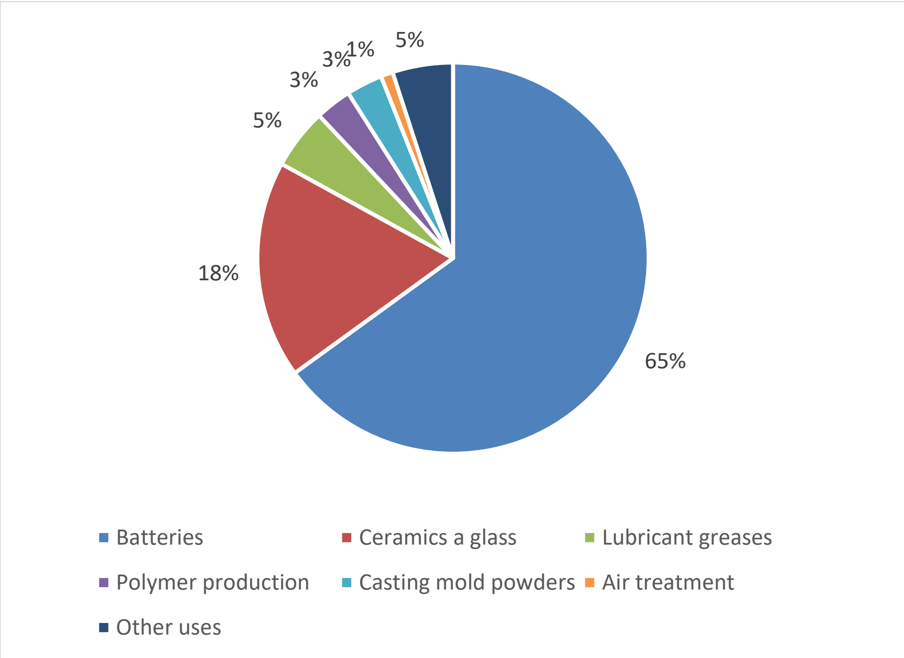

Figure 1. Lithium by end use in 2019 (Statista, 2019).

1.1.3 Lithium production

In 2018 only four countries in the World accounted for about 95 % of total World´s lithium production. These top four countries by production of lithium content in 2018 are as follows:

1. **Australia** - It produced 51,000 metric tons of lithium content in 2018, up an impressive 11,000 metric tons from the year before. The over 21 percent increase has been attributed to two new spodumene operations that ramped up production

in 2017, along with five additional spodumene operations that ramped up output in 2018. Production comes from hard rock deposits.

2. **Chile** - was another of the world's top producers in 2018, with its production increasing from 14,200 metric tons of lithium content in 2017 to 16,000 metric tons in 2018. Chile´s lithium comes from brine deposits.

3. **China** – The Asian country saw its lithium supply grow to 8,000 metric tons in 2018. While lithium production in China is comparatively low, it is the largest consumer of lithium due to its electronics manufacturing and electric vehicle industries. It also produces nearly two-thirds of the world's lithium-ion batteries and controls most of the world's lithium processing facilities.

4. **Argentina** - achieved production of 6,200 metric tons in 2018, which stands for increase of 500 metric tons to year before.

The latest data from the US Geological Survey shows that the world's top lithium producers are doing their best to meet rising demand from energy storage and electric vehicles — worldwide lithium supply rose roughly 23 percent from 2017 to 2018, coming in at 85,000 metric tons (MT) of lithium content last year, not including US production. If the electric vehicle market continues to grow, and if lithium-ion batteries continue their reign as the top batteries for electric vehicles, it's likely that they will produce even more of the metal in years to come. Lithium production in percentage per country is presented in **Figure 2**.

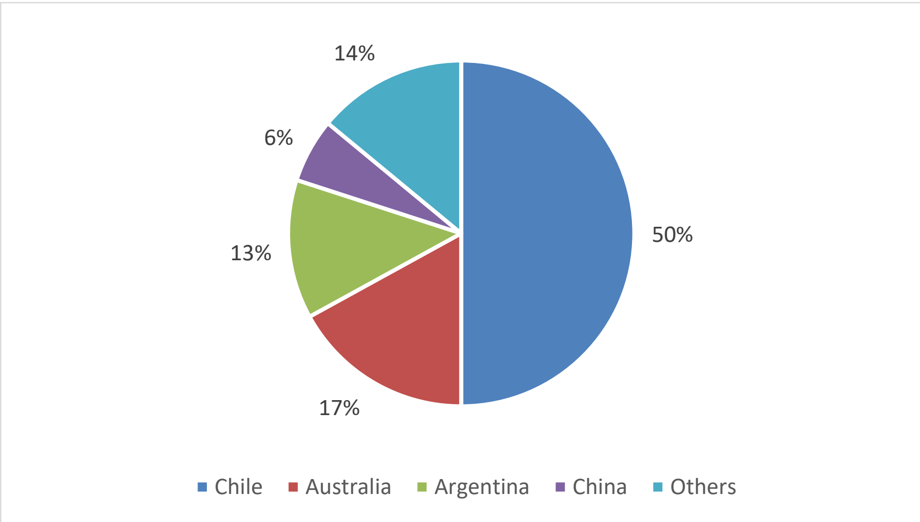

Figure 2. Lithium production by country in 2018 (Statista, 2019).

Only three companies called „Big Three" accounted for the 53% of world's lithium production in 2015 (Matich, 2015): Albermarle Corporation (NYSE:ALB), FMC Corporation (NYSE:FMC), and Sociedad Química y Minera de Chile also known as SQM

(NYSE:SQM). However, the list of the world's top lithium-mining companies has changed in recent years. The companies mentioned above still produce the majority of the world's lithium today, but the market share for the „Big Three" lithium producers has dropped from about 85 %.

China nowadays accounts for about 40 % of the world´s market share. The Asian nation was the third largest lithium-producing country in 2018 in terms of mine production, coming in behind Australia and Chile. China alone accounted for the 50% of the global total consumption of lithium in 2015 (Hao, Liu, Zhao, Geng, & Sarkis, 2017), being highly dependent on the spodumene concentrate imports from Australia. Top four lithium-mining companies by market capitalization are as follows:

1. **Tianqi Lithium -** Market capitalization around: 33 billion USD. Lithium producer Tianqi Lithium is a subsidiary of Chengdu Tianqi Group, headquartered in China. It is the world's largest hard rock lithium producer. Controls a majority of the Australia´s largest lithium mine called Greenbushes. Tianqi Lithium also holds a shares in other lithium mining companies and their operations for instance a 24 % share in SQM (Sociedad Química y Minera).

2. **Jiangxi Ganfeng Lithium -** Market capitalization around: 29 billion USD. Jiangxi Ganfeng Lithium is another important Chinese lithium producer. The company is China's second largest lithium producer, and like Tianqi, Ganfeng is also buying up interests in lithium companies outside of China. This Chinese mining company has interests in six lithium resources in Australia, Argentina, China and Ireland.

3. **Albemarle -** Market capitalization: 8 billion USD**.** Albemarle is one of the largest lithium producers in the world, with 5,000 employees and with customers in 100 different countries worldwide. The company owns lithium brine operations in the US and in the Salar de Atacama in Chile, and a 49 percent stake in the massive hard rock Greenbushes mine in Australia. In 2018 Albemarle also signed a deal to invest in a joint venture with Mineral Resources, which will own and operate the Wodgina hard rock lithium mine in Western Australia. Besides lithium, Albemarle produces bromine and provides refining solutions and chemistry services for pharmaceutical firms.

4. **SQM (Sociedad Química y Minera) -** Market capitalization: 7 billion USD**.** SQM claims to be the world's largest lithium producer, with offices in over 20 countries and customers in 110 nations across the globe. The firm has five business areas, ranging from lithium and derivatives to potassium to specialty plant nutrition.

While, market share of the largest lithium producers worldwide in 2017 by production is presented in **Figure 3**.

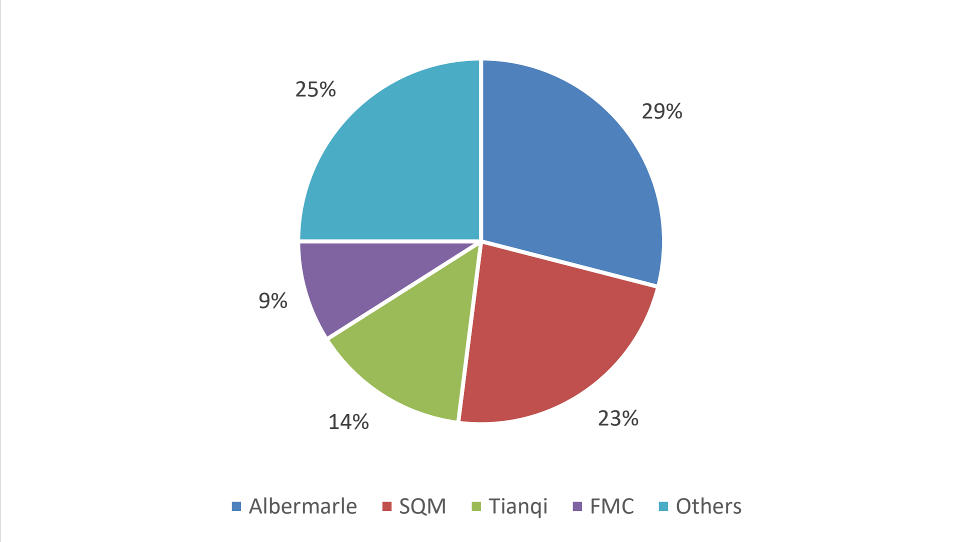

Figure 3. Market share of lithium producers in 2017 (Statista, 2019).

1.1.4 Lithium world reserves

Lithium on earth only occurs as a mineral compound in igneous rocks, subsurface lithium brines, lithium clays, or as a dissolved solid substance in seawater. So far, no project addressing seawater has been realized in a significant scale (Sverdrup, 2016). Apart from hard rock and lithium bearing clays, continental brine deposits, that are accumulations of saline groundwater enriched in dissolved lithium, represent about the 66% of global lithium resources. Most of them are located in salt flats in South America, mainly in Chile and Argentina, in the so called "lithium triangle", which accounts for half of the world's lithium reserves. A top four countries by lithium reserves in 2018 are as follows (Barrera, 2019):

1. **Chile –** with lithium reserves of 8,000,000 Mt is the number one by large amount. Chile holds the most of the world´s "economically extractable" lithium reserves. Its Salar de Atacama hosts approximately 37 percent of the world's lithium reserve base.

2. **Australia –** number one lithium-producing country but third in terms of reserves with 2,700,000 Mt.

3. **Argentina** – is the fourth largest producer of lithium metal and accounts for almost 2,000,000 Mt of reserves. Chile, Argentina and Bolivia comprise the "Lithium Triangle," which hosts more than half of the world's lithium reserves.

4. **China** – holds lithium reserves of 1,000,000 Mt and production is comparatively low to above-mentioned countries. China imports most of the lithium it needs from Australia.

While Chile, Australia, Argentina and China are home to the world's highest lithium reserves, other countries also hold significant amounts of the metal as well:

- Canada – 180,000 Mt,
- Zimbabwe – 70,000 Mt,
- Portugal – 60,000 Mt,
- Brazil – 54,000 Mt,
- United States – 35,000 Mt.

Overall, total worldwide lithium reserves stand 16,000,000 MT. If the metal continues to be as demanded as it is today, perhaps some of these countries with high reserves will play more important role in lithium production. Lithium world reserves expressed in percentage are presented in **Figure 4**.

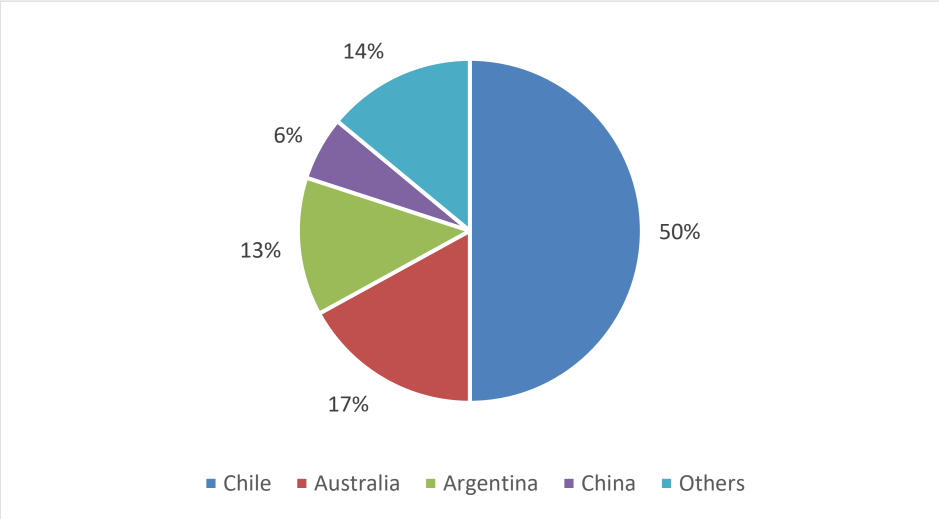

Figure 4. World Lithium reserves by country in 2019 (Statista, 2019).

1.2 Lithium mining and processing

Because of its reactivity, lithium does not exist in its elemental form in nature. While there are over 100 minerals that contain lithium, only three are currently mined commercially. These rock/minerals, that occur in pegmatites, are: lepidolite, spodumene, or petalite (Meshram, Pandey & Mankhand, 2014), being the spodumene bearing pegmatite deposits the most usual. On the other hand, recent mineral processing developments claim to allow the extraction and recovery of Li from lithium bearing micas such as lepidolite and zinnwaldite, that have largely been overlooked and were typically reported to tailings (Lepidico, 2018).

Lithium found in hard rock forms in crystals that are hosted in Pegmatites which form when mineral-rich magma intrudes into fissures in continental plates. As the last of this magma cools, water and other minerals become concentrated. These metal-enriched fluids catalyse rapid growth of the large crystals that distinguish pegmatites from other rocks. Pegmatites form thick seams called dikes that intrude into barren rock and can measure anywhere from a few to hundreds of meters.

Lithium concentration in the crust varies, but it is most likely between 17 and 20 parts per million (ppm). The abundance is normally 28-30 ppm in igneous rocks, but it can reach 53-60 ppm in sedimentary rocks.

Lithium-caesium-tantalum pegmatites account for about one-fourth of the world's lithium production, most of the tantalum production, and all of the caesium production. Giant deposits include Tanco in Canada, Greenbushes in Australia, and Bikita in Zimbabwe. The largest lithium pegmatite in the United States, at King's Mountain, North Carolina, is no longer being mined although large reserves of lithium remain. Some of the lithium bearing minerals are described briefly below:

- **Spodumene** is the most common lithium-bearing mineral found in commercial deposits. It can be found in granites and pegmatites as prismatic, lath-shaped crystals that are often intermixed with quartz. Spodumene has a Mohs hardness of 6.5–7 and a density of 3.1–3.2 g/cm3. It has a distinct longitudinal cleavage and weathers to form kaolinite and montmorillonite.

- **Lepidolite** is a rare type of mica found in pegmatites, with a Mohs hardness of 2.5-3 and a density of 2.8–3 g/cm3. Their crystals have a book-like form because to its lamellar cleaver age. Potassium, rubidium, and caesium can all be found in lepidolite, which can be lucrative by-products.

- **Petalite** is a monoclinic mineral with two directions of cleavage. It is frequently found in pegmatite sand with lepidolite, and there is evidence that it can change to spodumene in some situations. It has a hardness of 6 on Mohs scale and density of approximately 2.4 g/cm^3.

- **Eucryptite** and **Amblygonite** were once important lithium ores, especially in Zimbabwe, but deposits are now scarce, and the ore is today of little economic value.

- **Hectorite** is a clay mineral that forms when hydrothermal or hot spring activity alters volcaniclastic rocks. Within the mineral's lattice structure, lithium takes the place of magnesium. It is not currently extracted for lithium, however, it is anticipated that it will be in the future.

- **Jadarite** is a monoclinic, white borosilicate mineral that was discovered in Serbia in 2007. It is not currently extracted for lithium but has a strong potential to become an important source in the future.

The expression "brine" refers to any liquid with a high concentration of dissolved solids. Sodium (Na) and chloride (Cl) are the most common components of these solids, but calcium (ca), potassium (K), magnesium (Mg), and carbonate are also common (CO3). Lithium is found in a variety of brines and waters, but only in trace amounts. Lithium content, on the other hand, can be dramatically increased as the element is leached from the surrounding rocks, particularly in high-temperature geothermal waters. Lithium containing brines are derived entirely from the leaching of volcanic rocks. They range from highly concentrated lithium deposits in the high altitude salars of Chile, Argentina, Bolivia, Tibet and China where lithium concentrations are found to be really high; to mid-level brines like Silver Peak, Nevada and Searles Lake, California, to lower concentration brines like the Great Salt Lake, Utah. The brines with lower concentration have modest evaporation rates with constant dilution containing lithium in less concentration.

1.2.1 Mining methods

While lithium from hard rocks and clays is extracted by the use of conventional mining methods, brine deposits have, a priori, an advantage over them: the extraction of lithium is conducted by evaporation processes in man-made ponds, although the rate of enrichment obtained by solar evaporation is slow (Choubey, Kim, Srivastava, Lee, & Lee, 2016). On the other hand, recovery percentages do not differ a lot: 97% from brine deposits, and 94% from hard rock deposits (Alset Minerals Corporation, 2017; Pioneer Resources Limited, 2017).

Lithium brine production is currently derived from continental brine deposits. Lithium brine deposits, according to the USGS, are salty groundwater accumulations enriched in dissolved lithium. Despite their abundance in nature, brines can only be found in closed basins in arid regions where lithium salts can be extracted profitably. The following is how lithium brine evaporation works. Brine with a Li concentration of 200 to 1,400 mg/l is pumped to the surface and processed by evaporation in a series of artificial ponds, each with a higher Li concentration. A concentrate of 1 to 2 percent lithium is further processed in a chemical plant to yield different end products, such as lithium carbonate and lithium metal, after a few months to around a year, depending on temperature. For the production of metallic lithium, the carbonate is dissolved in hydrochloric acid which produces carbon dioxide that escapes as gas and lithium chloride in solution. This solution is reduced in a vacuum evaporator before lithium chloride crystallizes.

Hard rock mineral resources are more evenly distributed across the globe, with deposits found on every continent. In this case lithium compounds are not derived from salt of salt lakes but from lithium-containing minerals. However, only in a few locations in Canada, Australia, and China are currently developed hard rock deposits. Hard rock lithium mining relies on traditional methods of surface and underground mining. For deposits that are close to the surface (usually less than 100 m), surface (open-pit) mining methods are used. The overburden is usually removed as part of this process. The ore is dug up or blasted with explosives, then transported to a processing facility via trucks or conveyor belt. Material is extracted in layers, leaving horizontal benches along the sides of the surface mine so that the vertical faces can be worked safely. The stability parameters of the mined rocks determine the height of the faces. To enter shallow and deeper sections of an ore body, surface mining may be combined with underground mining. For example, both methods have been used for the world´s largest lithium Greenbushes mine in Western Australia.

Where open-pit mining is or becomes uneconomic, underground mining is used. For example, if the deposit is too deep or has a shape that can be efficiently mined using underground methods. An adit (horizontal), a shaft (vertical), or a decline are the most common underground access points to the ore body (at an angle). Ore is mined in stopes at varying depths below the surface on a variety of horizontal stages. Explosives are used to blast ore, which is then delivered to the surface through an underground rail system, dump trucks, or conveyor belt. Waste material is backfilled into old workings. A ventilation system plays an important role in mine safety and its operability.

Lithium bearing clays are typically found near the surface, thus open-pit methods are utilized to extract them. Normally no blasting is required as the clays are generally soft materials. At some localities an overburden must be removed. Mining of the clays is carried out in benches designed based on their parameters and properties in order to secure a safety during the mining. Various methods of transportation can be used such as dump trucks, conveyor belts etc.

1.2.2 Lithium Processing methods

Lithium processing methods vary based on the mineralisation and material from which is lithium obtained. Processing methods can be differed upon the type of deposit: hard rock, clay or brine.

1.2.2.1 Hard rock (spodumene) processing

As for the hard rock deposits a spodumene is the most common mineral its processing is described. The first step after extracting the lithium bearing ore is a process of beneficiation in order to increase the lithium content. This generally takes place in facilities close to the mine site and it involves crushing of the extracted ore and separation of the gangue (commercially valueless) minerals by physical and chemical processes. Minerals are physically sorted into concentrates based on their physical, electrical, and magnetic properties. Depending on the characteristics of the ore and gangue minerals, physical separation methods include wet and dry screening, as well as gravity, magnetic, electrostatic, and magneto hydrostatic separation. Lithium concentration can be increased by froth flotation, dense media separation, or a combination of the two. The lithium minerals are separated via froth flotation, which requires the use of water, chemicals, and compressed air. To make a suspension, water is first added to the powdered ore. Chemicals are used to make specific minerals water resistant and induce air bubbles to adhere to their surfaces after air is blasted upwards through the tanks. As a result, these minerals froth up to the surface and are washed away. Dense media separation (DMS) uses heavy liquids of appropriate density to separate minerals that are lighter than the liquid and those that are denser. Flotation may not be required if the deposit is coarse-grained, and a concentrate can be generated using simply gravity separation methods. A common lithium carbonate concentrate will have 6-7 percent Li_2O (75-87 percent spodumene), whereas a higher-grade concentrate used in ceramics and other applications that require certain chemical standards will include about 7.6 percent Li_2O.

After physical beneficiation yields a lithium concentrate, further processing is necessary to generate lithium compounds or lithium metal. Different methods for recovering lithium from its ores have been proposed, but the acid leaching procedure is the most extensively employed. First stage of the leaching is to convert naturally occurring spodumene to β – spodumene by heating at 1050 °C for about 15 minutes causing the transformation from monoclinic structure to tetragonal crystal lattice so the spodumene became available to leaching. Because the crystal lattice expands during roasting, the mineral becomes less dense, allowing the lithium to be chemically removed.

The first step in the β – spodumene acid leaching is to generate lithium sulphate by roasting a combination of finely ground spodumene and sulphuric acid at 250 °C. After this a lithium is separated by leaching. Impurities such as iron, aluminium, and magnesium (which is also transformed to the sulphate form) are removed by dissolving the lithium sulphate in water and then separating the liquid from the solid through filtration, yielding a lithium sulphate solution with trace amounts of magnesium and calcium as the only significant impurities. To precipitate insoluble lithium carbonate, the purified lithium sulphate solution is treated with sodium carbonate. Before being sold or utilized as feedstock in the manufacturing of additional lithium compounds, this product is dried. This method can produce lithium carbonate grades of up to 99.3%, however for battery grade (99.5 percent min. Li2CO3), additional processing such as bicarbonation is required.

Carbonate leaching is an alternate process that includes mixing the β spodumene concentration with water to form a fine-grained slurry. In a pressure vessel, this combination is reacted with sodium carbonate at 215 °C and 2140 kPa, followed by the addition of carbon dioxide to convert the insoluble lithium carbonate to the more soluble bicarbonate. Contaminants including salt, aluminium, and iron are precipitated out at this stage with the right reaction conditions. After that, the lithium carbonate product is precipitated by removing the excess carbonate, which is subsequently recycled. Another option is to use lime to leach the spodumene (CaOH2). The spodumene ore is combined with finely powdered limestone and heated to 900 to 1000 °C in this process. During this process spodumene changes to β - form. After that, the lime reacts with the β - spodumene to produce dicalcium silicate and lithium oxide. The clinker is then crushed and ground before being leached with hot water to produce lithium hydroxide, which is then separated, washed, and dried as a finished product. By reacting lithium hydroxide with HCl acid, lithium chloride can be produced.

1.2.2.2 Lithium clays processing

There are many approaches possible for extracting lithium from clays. The choice of which approach to follow depends upon the nature of the specific raw material being considered. As the lithium-bearing clays are not widely commercially mined, therefore it is difficult to obtain any information. A suggested method of processing is described based on the preliminary feasibility study of Lithium Nevada. The dry ore preparation stage consists of crushing and grinding the ore, as well as two reagents, anhydrite and dolomite, which are blended and blended in a granulator. The granules would next be dried, calcined, and chilled. The second stage, a wet recovery process, would entail leaching the calcium with water at 70 degrees Celsius to produce a brine from which calcium, potassium sulphate, lithium carbonate, and sodium sulphate would be precipitated in succession. Following the addition of sodium carbonate, the lithium carbonate would precipitate, and the resultant crystals would be cleaned, filtered, and dried before being packed. This approach is projected to have an 87.2 percent lithium recovery rate. Techniques for extracting of lithium from clays are still being tested, some of the tested methods are: water disaggregation, hydrothermal treatment, acid leaching, acid baking-water leaching, alkaline roasting-water leaching, sulphate roasting-water leaching, chloride roasting-water leaching and multiple-reagent roasting-water leaching. However, there is still not enough information to confirm an effectivity of all tested methods.

1.2.2.3 Brine deposits

The Continental brine deposits are the main source of lithium today. The methods for processing brines will vary depending on the chemistry present at each deposit. In order to extract lithium from brines, the salt-rich waters must first be pumped to the surface into a series of evaporation ponds where solar evaporation occurs over a number of months. Because salar brines occur naturally at high altitudes – and in areas of low rainfall – solar evaporation is an ideal and cost-effective method for precipitating salts Nonetheless, concentrating the brines will always be the initial step. Because the brines have relatively low lithium content, this is a key phase in their processing. In most cases this process takes place in in series of surface located solar evaporation ponds.

Because lithium is more soluble than other elements in brines, compounds like sodium chloride, potassium chloride, and calcium sulphate will precipitate first, leaving the brine more concentrated in lithium. The lithium will eventually precipitate as lithium chloride, although the concentrated brine is frequently collected for further processing prior to the stage. To avoid the precipitation of undesirable chemicals, the evaporation process must be closely monitored. The pond must be large and leak-free in order for sunlight evaporation to be efficient. Normally, the ponds are either clay-sealed or coated with an impermeable plastic membrane. The process depends highly on amount of solar radiation, humidity, wind and temperature. These factors may have a great impact on the operating costs and other processing parameters such as pond size or final brine concentration and treatment methods.

As the brine becomes more concentrated in lithium, it is pumped through a series of evaporation ponds. The sequence of ponds is as follows:

Sodium chloride (common salt) is precipitated first. It's possible to harvest it as a by-product. The brine is then moved to a second set of ponds where a mixture of sodium chloride and potassium chloride is precipitated at the desired concentration. These are gathered and split into two components in a flotation plant. The residual brine is then transported to a new set of evaporation ponds, where it will remain until the Li concentration reaches at least 6000 parts per million. After that, it's taken to a rehab facility. The boron and magnesium content of this brine may be increased. Boron is extracted using kerosene as a solvent and processed into borates and boric acid by-products. Magnesium must also be removed because it raises the cost of making lithium carbonate. This is accomplished by first precipitating magnesium carbonate with sodium carbonate. The magnesium hydroxide is then precipitated by adding lime..

To make a lithium carbonate slurry, the lithium-rich brine is treated with sodium carbonate. To eliminate any remaining sodium chloride, this is filtered and then washed with water. Finally, the product is dried, yielding a 99% pure lithium carbonate. Brine that hasn't been used is reinjected into the salars.

By-products especially potash and boron minerals are also produced from lithium-bearing brines. These by-products can make a big difference in the project´s overal profitability.

Commercially available lithium compounds include lithium carbonate, which is the most extensively used and accounts for more than 90% of total consumption. Lithium carbonate is a stable white powder which is a key intermediary in the lithium market because it can be converted into specific industrial salts and chemicals — or processed into lithium metal.

Lithium hydroxide, butyl-lithium, lithium metal, and lithium chloride are some of the other forms of lithium with considerable industrial use. Processing lithium carbonate yields the majority of the accessible chemicals. The manufacture of lithium metal and its compounds is an exception to this rule. A combination of molten lithium chloride and potassium chloride is electrolyzed to generate lithium metal.

Lithium production is either tedious or expensive. Recently, more and more exploration and development companies have been relying on new technologies to help them extract lithium from brine deposits within days and even hours, rather than by means of natural evaporation, using specially developed processes in corresponding plants.

2. OBJETIVOS

There are two main objectives of this thesis. First objective is to carry out an evaluation of lithium mining projects in different countries around the World (Canada, Mexico, Argentina, Finland, Australia). This evaluation should provide general information and understanding of the lithium mining. Information and relations obtained from this analysis will be further used as a tool to simplify an evaluation process of mining project elaborated in this thesis. The second objective of this thesis is the evaluation of the Cínovec lithium deposit situated in Czech Republic. Result of the thesis will determinate viability of the Cínovec lithium project within the accuracy of scoping study. These two objectives will be achieved through several sub-objectives. First objective a **Lithium mining industry analysis** is composed of following sub-objectives:

- Obtain a complex understanding of the international context of lithium production and commercialization.
- Analysis of five lithium projects around the World.
- Identify a ideal cut-off grades for lithium project.
- Determine dilution and extraction ratios.
- Metallurgical recovery generalisation.
- Determine formula for Capital expenses estimation.
- Determine operating expenses for lithium mining project.
- Set up relation between economic outcomes of lithium mining projects.

Second objective: **Cínovec project evaluation** and it´s Sub-objectives:

- Area mapping and description.
- Drillhole database collection and analysis.
- Resource calculation and estimate.
- Creation of block model with suitable computer software.
- Open pit design and production parameters determination.
- Economic analysis.
- Sensitivity and Uncertainty analysis.

When all these objectives and sub-objectives are completed a final conclusion is presented. Conclusion of this thesis shall determine a viability of a proposed lithium project. Under no circumstances conclusions presented within this thesis can be considered as a professional or any other advise (nor investment, tax, accounting or legal advice) and has been prepared without taking account of any person's investment objectives, financial situation or particular needs.

3. DISCUSIÓN DE RESULTADOS

3.5 Cínovec waste pond deposit project

Another mining company Cínovecka deponie a.s. (CD) considers a possibility of lithium exploration in Cínovec area at the moment. In order to produce lithium, the company wants to exploit a waste pond created during the mining operations in the past.

During the rich history of mining in the Cínovec area a significant amount of waste material produced during the underground mining was stocked at the surface. At the time of underground mining in the Cínovec area this material was considered to be waste with no added value. However, as the circumstances changed and lithium became an important metal, there are serious affords towards exploiting a lithium from these waste pond. Material stocked at the surface contains also a significant amount of Caesium and Rubidium. Compounds of these Alkali metals have a significant technological potential in improving batteries parameters, solar panels manufacturing and catalytic converters.

All necessary legal issues are solved and all permits needed to commence the mining operations were issued. Nevertheless, the CD company is more as a developer than mining company, therefore CD is looking for a partner (mining company) that would participate in the project. This project represents an interesting opportunity as a major parts of production process (mining and milling) have already taken place and the lithium containing sand is basically ready for magnetic separation. This material could be also used as an input for a pilot test plant for purposes of improving a knowledge on metallurgical recovery for purposes of the Cínovec project.

3.5.1 The Cínovec waste heap project

The input material in Cínovec waste heap (waste residuum of previous mining) consists basically of silica sand, which contains high proportion of magnetic micas with contents of lithium, rubidium and caesium. Ponds also contain some proportions of potassium, scandium and tungsten. Cínovec waste pond contains approx. 0.98 Mt of input material and it is spread over mining area of 8.6 ha. However, approximately 30 % of the deposit is blocked due to Environmental Impact Assessment (EIA) as there are protected marshes in the area.

Geological survey of Cínovec waste pond site was conducted by Geomet company (subsidiary of EMH) in 2013. Deposit mapping, volume of raw materials and its homogeneity is based on detailed reports of historical tin mining (1960s – 1990), 16 sample boreholes (1990-2012) and geological maps and morphological terrain structure. Based on available data volumes in **Table 36** are estimated for the Cínovec waste pond deposit.

Table 4. Cínovec waste pond volumes (Geomet, 2013)

Input material volume	**(t)**
Total volume of input material	977 307
Material blocked due to EIA	-180 664
Material blocked due to dam	-117 000
Available volume of input material	**679 643**

The total available input material that could be extracted from the waste pond is 679 643 t. Balance of material is presented in **Table 37.**

Table 5. Cínovec waste pond (Geomet, 2013)

Quantity of raw materials recoverable from the input material	**Volume (tonnes)**	**Concentration (%)**
Silica sand	507 014	74.6
Mica concentrate	148 162	21.8
Waste	24 467	3.6
Total	**679 643**	**100**

The highest concentrations of special-interest metals are found in the mica concentrate. This concentrate can be treated in order to obtain lithium, rubidium, caesium and potassium carbonates, scandium oxide or tungsten powder. Based on previously conducted laboratory test works, wet magnetic separation method is considered as the most effective in the separation of the mica concentrate from input raw material.

The processing of input material will consist in extraction and subsequent two-stage wet magnetic separation. The process will be carried out by using mechanical and physical methods without any chemical substance. The mining of the input material will be carried out by the conventional truck and shovel mining method. Both mining and processing (separation) will be carried out at the site in order to reduce operational expenses.

3.5.2 Mining and production parameters

3.5.2.1 Mineable reserves

The total volume of the reserves on the Cínovec waste pond deposit is 860 307 t. Taking into account mining losses of 21 % estimated by the CD company (8% extraction ratio and 13 % dilution) a total amount of mineable reserves is 679 643 t. Given the deposit area 5,6 ha an average thickness of the material layer of 9 m is considered for the deposit.

3.5.2.2 Extraction ration and mining dilution

In the waste pond area, there are layers of clays and sand-clays, which arose during the process of sedimentation of sludge material. These layers of approximately 0.5 m thickness must be removed prior mining. These layers account in total of approximately 13 % of the deposit (mining dilution).

More clays and sand-clays layers are located at the edges of the deposit towards a dam protecting the marshes. These accounts for approximately 3 % of the deposit. Layers located at the bottom of the seam are quite diluted. During the process of waste pond sedimentation, no isolation materials were used to separate the soil from sludge material. All the material was spread over the original not flattened soil. Deposit extractability is reduced by this to 92 %. Thus, the total mining losses are estimated at 21 % (extraction ratio 92 % and dilution 13%).

3.5.2.3 Mining method

There will be almost no overburden removal required at the area. Only stumps with roots must be removed in minimum thickness approx. up to 0.3 m. If during mining operations the occurrence of a greater thickness of recoverable materials is detected, (which was not recorded by geological prospecting), these materials will be extracted separately and stoked in the area defined as "operational pillar". This material will be subsequently used for reclamation purposes.

The mining operations will be carried out by conventional truck and shovel method with several benches. The proposed mining method for Cínovec waste pond deposit is based on geological and mining conditions, which include factors such as: geological structure, height of individual benches, geo-mechanical properties of soils, height of aquifer, horizon of planned utility roads etc. There will be no blasting operations at the site.

The mining will be carried out by bench mining method with use of loaders and excavators. In total three benches are proposed for the mining process. After the removal of the overburden soils nonrecoverable material (stumps, roots etc.) two benches will be created in order to extract lithium bearing clays. Each of these two benches with maximum height up to 6 m with an angle of 45 degrees and minimum bench width of 10 m. Finally, the bottom layers will be reach by the third bench.

The material will be loaded by excavators or loaders on the trucks and transported to the processing facility. During the process of mining, it is important to take into account a possible aquifer. As a result of the aquifer at the deepest part of the mining location a water pond or drainage must be created in order to dewater the mine site. The water from the mine site can be used as a technological water during the processing. Pre-mining situation and aerial view of the mine site is presented in **Figure 43** and **Figure 44**.

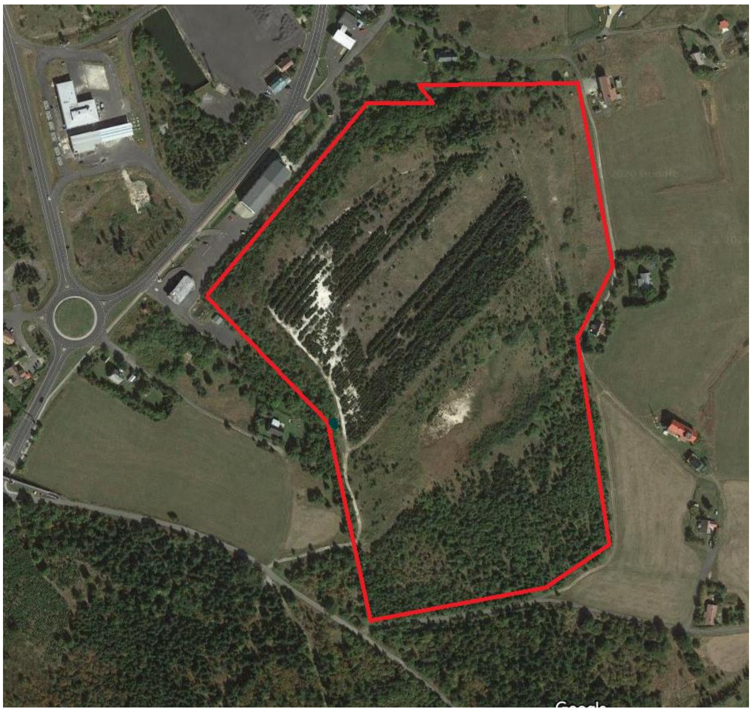

Figure 5. Aerial view of the Cínovec waste pond mine site.

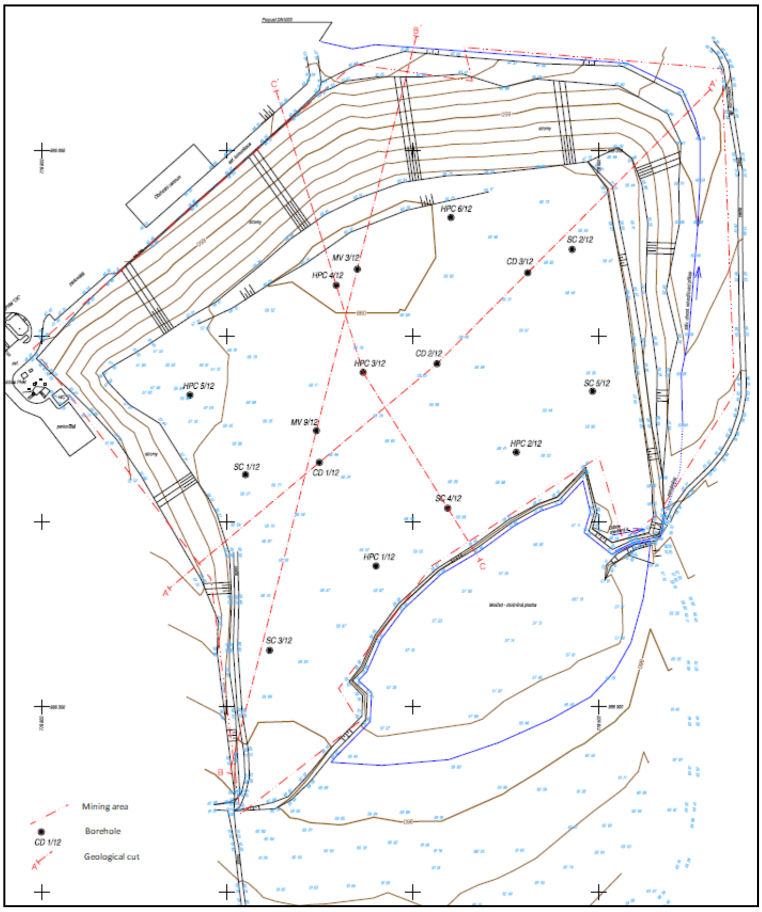

Figure 6. Pre-mining situation at the Cínovec waste pond

The final shape of the pit at the end of the mining operations is presented in **Figure 45**. Blue, red and green line presents a stages of deposit exploitation process. First and Second benches are designed to be 6 m height and the third will be mined in approximately 2 m heigh.

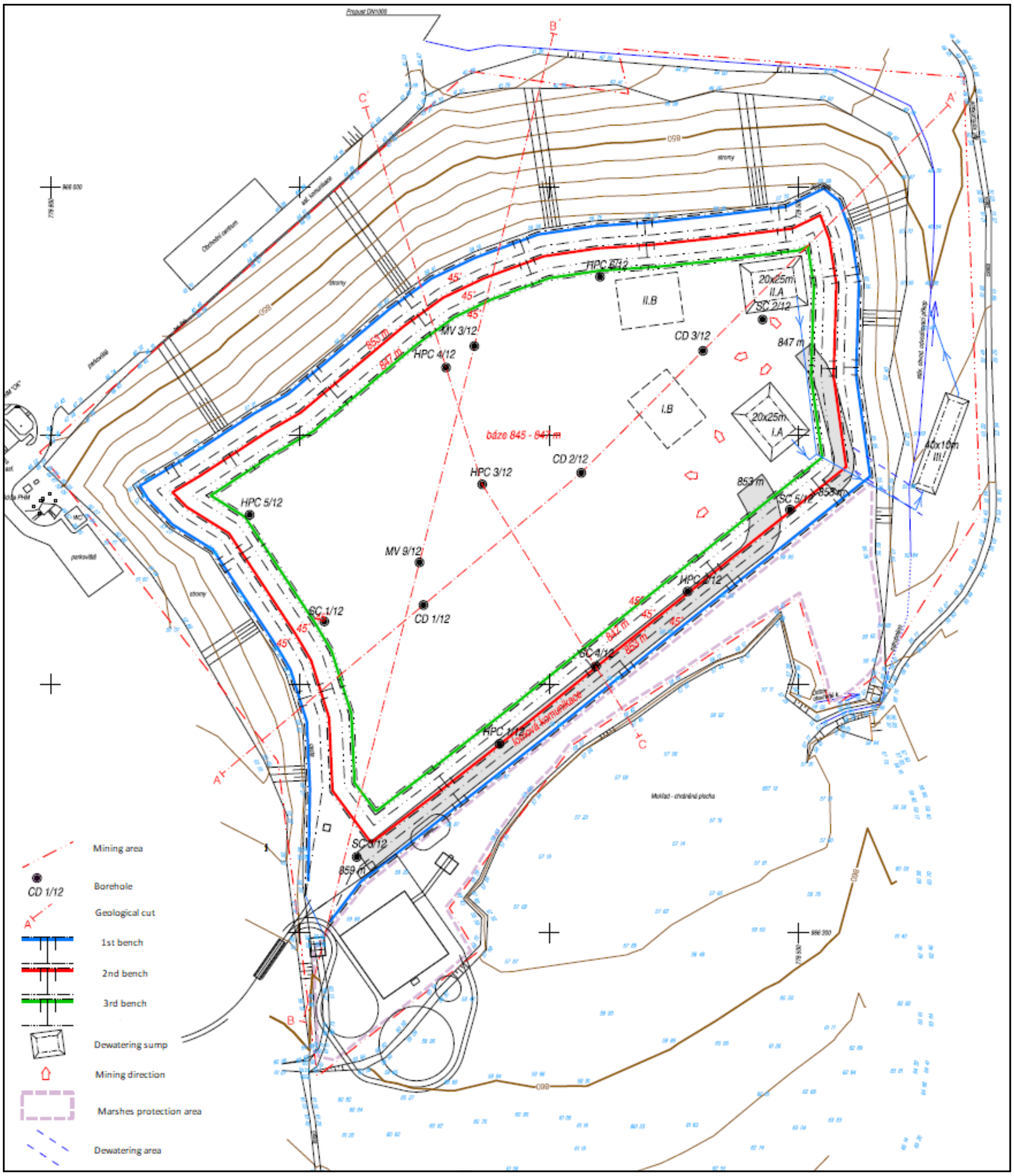

Figure 7. Open pit design for the Cínovec waste pond

3.5.2.4 Mining infrastructure

Following mine site infrastructure will be needed for smooth process of lithium clays extraction:

- Residential containers in order to provide a facility for site management.
- Separation line where the extracted material from the waste pond will be processed into the zinnwaldite sand.
- Road weight to provide information about the amounts of material transported from the mine site.
- Access roads and electricity lines for the mining and processing activities.
- Water reservoir in order to secure a mine site water management.

3.4.2 Processing method

First step of the processing will be a wet magnetic separation. This process aims to produce a zinnwaldite concentrate. Effectiveness of the separation process is expected to be approximately 60 %. (Sanaka Industry, 2020) Separated sand can be considered due its properties as a by-product with added value for glass production industry.

Processing plant will produce a Lithium carbonate (Li_2CO_3), also Rubidium carbonate (Rb_2CO_3), Potassium carbonate (K_2CO_3), Caesium carbonated, tungsten or Scandium oxide can be also retrieved. Processing of the zinnwaldite concentrate can be done by gypsum method or alternatively by limestone method, both of them were tested by University of Chemistry and Technology in Prague (Jandova, Hong N., Belkova, Dvorak, Kodas, 2009)

1. **Gypsum method** – Thermal decomposition of ore is achieved by application of gypsum and calcium hydroxide mixture at temperature between 940 to 960 °C. Lithium is transformed into solution as Li_2SO_4 precipitate to Li_2CO_3 by reacting with Na_2CO_3 or K_2CO_3. The same process can be applied for Rubidium metal. The main advantage of this method is a high recovery of Li, while as a disadvantage can be considered a need for higher temperatures during roasting.

2. **Limestone method** – limestone is used for thermal decomposition at temperature around 820 – 830 °C. Lithium is transformed into solution as LiOH and by reaction with CO_2 lithium carbonated is made. The same process can be applied for Rubidium. Released CO_2 in the process is used for precipitation of carbonates. This method can deliver higher efficiency for rubidium recovery at lower temperature, on the other side a CO_2 emission are produced in this process.

Simplified technology scheme for both methods is presented in **Figure 46.**

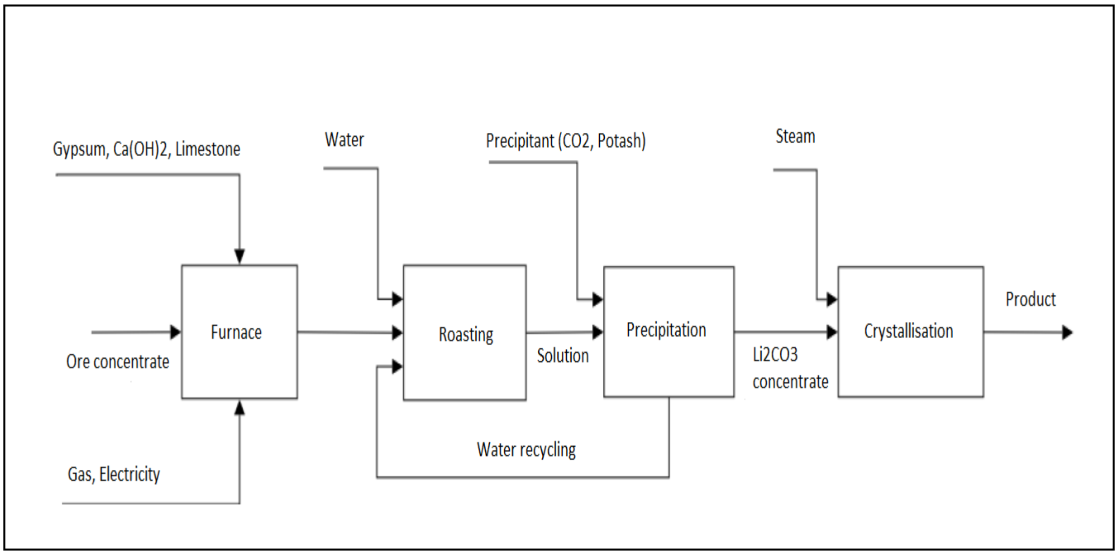

Figure 8. Technology scheme for processing methods

3.4.3 Project visualization

Figures 47 to 49 shows a visualization of the Cínovec waste pond location and proposed open pit including the processing facility (separation line).

Figure 9. Visualization of the mining pit. (Sanaka Industry, 2020).

Figure 10. Visualization of the mining pit – side view (Sanaka Industry, 2020).

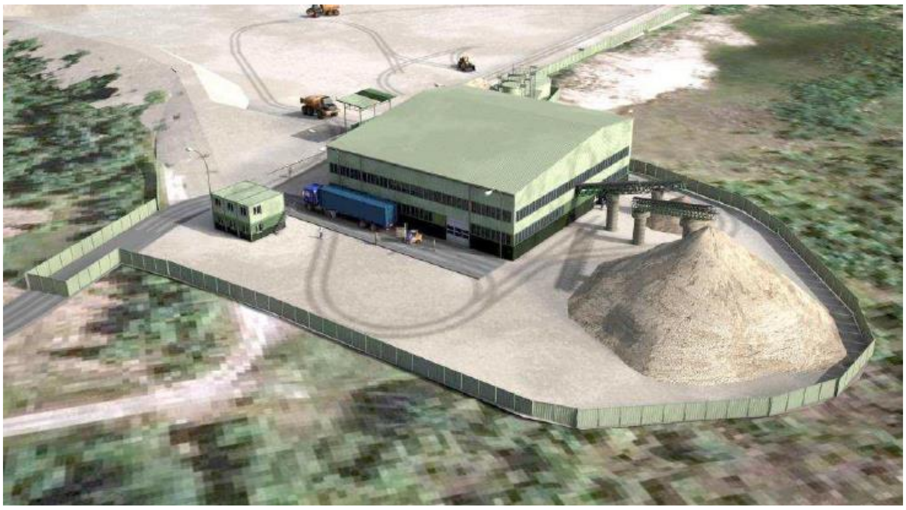

Figure 11 Cínovec wastepond processing facility (Sanaka Industry, 2020).

Figure 12 Cínovec wastepond processing facility (Sanaka Industry, 2020).

3.4.4 Economic evaluation of Cínovec waste pond project

Within this section, a quick economic evaluation of the Cínovec waste pond project was conducted. Similar variables and approach were used as in case of evaluation of the Cínovec project. Based on available information on the project, following variables were selected:

- Life of Mine – 6 years
- Capital cost – 18 000 k$ mainly consist of the investment into the wet magnetic separation line
- Stripping ratio– rounded to 0 as there is almost no overburden
- Dilution – estimated at 5%
- Extraction ratio – estimated at 100%
- Metallurgical recovery – same as the Cínovec project 70%
- Total material mined – 150 (kt/year)
- Total ore – 150 (kt/year)
- Average % Li – rounded to 0,13%
- Average % Li – after dilution 0,12%
- Lithium per year – 0,19 (kt/year)
- Lithium carbonate per year – 1,00 (kt/year)
- Mining costs – same as the Cínovec project 7 ($ t/ore)
- Processing costs – same as the Cínovec project 55 ($ t/ore)
- Price of lithium carbonate – estimated 10 000 ($/t)
- Amortization – amortization calculated for period of 20 years at 5% per year
- Royalties – 480 ($/t Li)
- Taxes – 19%
- Discount rate – 8%

Table 38 shows the calculations of the cash flow for the initial year (year 0) and for the rest of the years of the project (year 1-20). In order to simplify the model, inflation was not considered. Constant euros of 2020 were used instead of current euros, assuming that prices will grow the same as the inflation rate. Thus, costs and revenues will remain stable during the years considered for the calculations.

The after-tax Net Present Value of the project was calculated **negative**. A negative NPV indicates that the **project will not exceed anticipated costs** and will not be profitable. Thus, the Internal Rate of Return nor Payback Period were obtained.

Table 6 Cash flows calculation Cínovec waste pond (k$)

	Year 0	Years 1-6
Capital costs	(18 000)	
Working capital	(2 348)	
Mining costs		(1050)
Processing costs		(8250)
Royalties		(90)
Total costs		**(9 390)**
Revenue		**10 000**
EBITDA		610
Amortization		(900)
Pre-tax benefit		(290)
Taxes		(55)
Post-tax benefit		(345)
Cash Flows	**(20 348)**	**(555)**

The main reason for the negative result of NPV is the initial investment needed for the on-site wet magnetic separation line. Such an investment is rather inadequate to the amount of the material disponible at the waste pond deposit, even thought the amortization period is considered for 20 years instead of only 6 years. The decision to calculate amortization for 20 year period was based upon fact that this separation plan would serve for further exploration of the Cínovec project as well. Nevertheless, the Cínovec waste pond deposit project offers a unique chance for pilot project of the separation line and possibility pilot project for the metallurgical processing plant as both have not yet been tested in industrial scale. Also, it is important to mention that conclusions within this thesis cannot be considered in any way as professional advice or an investment recommendation but only as an academic exercise.

4. CONCLUSIONES

El trabajo desarrollado durante esta tesis doctoral, ha permitido alcanzar las siguientes conclusiones:

1. Es posible establecer una relación lineal ente el monto de la inversión en M$ de un proyecto de minería de litio y su producción anual de carbonato de litio kt/año, con independencia de que la explotación sea subterránea o a cielo abierto. El R^2 es de 99,99%.

2. Se estableció una comparación entre el comportamiento del mercado del litio y la evolución del mercado del óxido de disprosio, así como el desarrollo de análisis de series de tiempo de los precios del litio. Se espera que regresen a un comportamiento más estable (por debajo de 10.000 $ / t) a pesar de la creciente demanda, basado principalmente en: (1) un aumento de la producción por parte de los mineros, (2) el retorno a un equilibrio de oferta y demanda con precios fijados por los costos mineros con márgenes normales del mercado minero, y (3) el hecho de que hay suficiente litio recursos recuperables para asegurar la demanda de futuros vehículos eléctricos.

3. Se analizaron los aspectos económicos y técnicos de los diferentes proyectos de inversión en minería de litio, lo que permitió dar un orden de magnitud de esta industria minera para facilitar el desarrollo de la evaluación económica preliminar de futuros proyectos mineros: leyes de corte, dilución y ratios de extracción, recuperaciones metalúrgicas, gastos de capital y gastos operativos.

4. Como resultado del análisis de proyectos mineros de litio se destaca un aspecto importante: las salmueras continentales, donde la extracción de litio se lleva a cabo mediante el proceso de evaporación en estanques artificiales, no presentará una salida del mercado para el litio extraído de rocos y arcillas duras utilizando métodos de extracción convencionales, ya que tienen casi los mismos costes operativos.

5. Se observó que los resultados financieros de los proyectos evaluados de extracción de litio lograron unos valores de VAN y TIR inferiores a los esperados, ya que los precios pronosticados de LCE que se utilizaron fueron muy conservadores en la mayoría de los casos. El uso de una tasa de descuento del 8% en lugar del coste medio ponderado real del capital compromete la confiabilidad de los VAN presentados.

6. El mineral extraíble del proyecto Cinovec tiene un promedio de 0,52% de Li_2O, un valor que es sensiblemente más bajo que el resto de los proyectos que se analizaron dentro de la tesis, utilizando un grado de corte similar de 0,4% de Li_2O.
7. El proyecto Cinovec explotará las micas de litio, algo que puede representar una desventaja para la tecnología convencional de tostado con supfato de sodio hasta que se pruebe a nivel industrial.

8. El diseño de cono óptimo para la minería a cielo abierto propuesto en la zona de Cínovec es extremadamente cercano a un área habitada, esto disminuye considerablemente la posibilidad de desarrollar la explotación a cielo abierto.

9. Los resultados financieros del proyecto Cinovec son los más bajos de todos los proyectos analizados dentro de la tesis, a pesar del uso de una estimación más alta de los precios del carbonato de litio, excepto en el caso de Cauchari-Olaroz. Además, el análisis de incertidumbre no es favorable para el proyecto, ya que reduce el valor más probable del VAN casi a cero. Por otro lado, la pequeña desviación estándar indica que los valores posibles del VAN tienden a ser cercanos a cero.

10. Es importante enfatizar que dentro de la evaluación solo se consideró el litio y no los subproductos que también se pueden explotar, principalmente el estaño y el tungsteno. Sin embargo, el proyecto podría mejorar considerablemente si se incrementan los recursos, ya que existe un área amplia con baja densidad de prospección y más de 400 Mt de recursos inferidos.

11. El proyecto de escombrera de Cínovec ofrece una oportunidad interesante para un mayor desarrollo del proyecto de litio de Cinovec. Este proyecto de escombrera podría servir potencialmente como un proyecto piloto donde se podría obtener información más detallada, especialmente sobre el método de recuperación metalúrgica en la aplicación a escala industrial. Esto es importante ya que, según el análisis de sensibilidad, la recuperación metalúrgica tiene el segundo impacto más alto (el precio del carbonato de litio tiene el primero) en el VAN de los proyectos mineros de litio.

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