Lithium mining: accelerating the transition to sustainable energy

Abstract

In the actual context of climate change threats, lithium batteries fulfil lot of expectations in order to achieve a cleaner and more sustainable solution for transports, embodied by electric vehicles. According to different studies that identified a noticeable discrepancy between consumption and production, undersupply should be expected until 2045 in the European Union. Thus, ensuring lithium supply for the growth of energy-sustainable industrialised countries is crucial, and different approaches should be undertaken as for the purpose of technological transition, time matters.

This paper focuses in analysing lithium prices and their expected evolution. It also studies in deep five ready-to-go lithium mining investment projects worldwide: Whabouchi Project in Canada, Keliber Project in Finland, Cauchari-Olaroz Salars Project in Argentina, Sonora Project in Mexico, and Pilgangoora Project in Australia. The main purpose being to provide an exhaustive analysis of lithium mining investment in order to facilitate the development of preliminary economic assessments of future mining projects, fighting again supply disruption and accelerating the transition to sustainable energy.

Conclusions state in first place that prices are expected to return to a more stable behaviour, mainly based on a ramping up of the production by miners, as there are sufficient lithium recoverable resources in order to ensure the demand of future electric vehicles. Moreover, recycling of lithium batteries will represent a significant supply for the future.

In second place, an order of magnitude both technical and economic of this mining industry is given. Two aspects can be highlighted: (1) it was possible to establish a linear correlation between the capital expense of the lithium mining investment projects and their expected production of lithium carbonate; and (2) continental brine deposits, where the extraction of lithium is conducted by evaporation processes in man-made ponds, will not represent a push out of the market for the lithium extracted from hard rocks and clays using conventional mining methods as they have almost the same operating costs.

Keywords

Lithium, Mining project, Preliminary economic assessment, Sustainable energy, Batteries, Electric vehicle

1. INTRODUCTION

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. 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.

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). Although there are more than 100 minerals containing lithium, only three of them are commercially mined today. 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).

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.

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).

Martin, Rentsch, Höck & Bertau (2017) estimated lithium world resources in 34 Mt, and lithium world reserves in 14 Mt, accounting for a static range of 435 years. Due to the huge lithium resources and reserves, lithium from secondary sources (recycling) has nowadays no significant impact on the global supply so far (Martin et al., 2017). Some scenarios predict a 25% supply substitution by 2050, with the biggest potential focused on the recycling of lithium batteries (Reck & Graedel, 2012). Addressing lithium compounds substitution, it is possible in batteries, greases, ceramics, and manufactured glass (U.S. Geological Survey, 2019).

Growth of lithium importance is highlighted by the British Geological Survey (2015) in their metal risk list. This list evaluates the supply risk index of metals according to several factors such as production, concentration, distribution, substitutability, etc. In a scale from 1 to 10, lithium has been ranked with an index of 7.6, the same as the platinum group elements, increasing its index from a 5.5 in 2011, and a 6.7 in 2012.

The Swedish Agency for Growth Policy Analysis (2016) also considers lithium as a required innovation-critical metal, addressing vehicle electronic energy storage. This report points out as well potential synergies between battery factories and the extraction of lithium for the cathodes and graphite for the anodes in Sweden. Daw (2017) also considers lithium as a critical raw material for France.

The European Union included lithium for the first time in 2013 on its critical raw material list due also to its high supply risk linked to environmental performance (Chapman et al., 2013). Nevertheless, in the Report on critical raw materials for the EU from 2014, lithium was removed from the group of critical raw materials due to a non-critical supply risk according to the poor governance indicator, although close to the threshold (European Commission, 2014). Nothing has changed since then (European Commission, 2017).

Global production of lithium has more than doubled over the last two decades from approximately 15,000 t in 2001 to more than 35,000 t in 2016 (Golden Dragon Capital, 2016) and to 69,000 t in 2017, with an estimation of 85,000 t for 2018 (U.S. Geological Survey, 2019). World top four producers of lithium were in 2017: Australia (40,000 t), Chile (14,200 t), China (6,800 t) and Argentina (5,700 t) (U.S. Geological Survey, 2019). In year 2015, only three companies accounted for the 53% of world's lithium production (Matich, 2015): Albermarle Corporation (NYSE:ALB), FMC Corporation (NYSE:FMC), and Sociedad Química y Minera de Chile (NYSE:SQM), but this situation is quickly changing.

Over the last 10 years China also became an important player in the lithium market, controlling nowadays around the 40% of the market after reducing the oligopoly of these companies from an 85% in 2004. 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.

There are several lithium compounds produced worldwide, but only two of them are most widely commercialized: lithium carbonate (Li_2CO_3), for either industrial or batteries applications, and lithium hydroxide (LiOH), 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-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).

Lithium´s potential goes further than just for batteries. In fact, batteries represent only the 56% of the global consumption of lithium (U.S. Geological Survey, 2019), although a huge increase in the share is forecasted for the near future. This trend goes hand by hand with an increasing production of electric vehicles (EV) worldwide. Only in 2016 worldwide plug-in EV sales were 773,600 units, which represent a 42 % more than in 2015 (EVvolumes, 2017). Demand is driven by several battery-factory projects currently under construction or recently completed, such as Tesla´s Gigafactory (Matich, 2015). On the other hand, Tesla alone aims to produce up to 500,000 EVs per year by the end of the decade.

Another considerable part of lithium market still belongs to glass and ceramics industry, representing another 23% of global consumption. Further uses of lithium are: lubricating greases (6%), air treatment (2%), continuous casting mould flux powers (3%) and polymer production (4%), and others (6%) (U.S. Geological Survey, 2019).

Addressing rechargeable batteries, there are four main types: lead-acid (LA), nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and Li-ion. Li-ion batteries are replacing commonly used lead and nickel based batteries due to many aspects, such as: higher specific energy (up to 3 times more than NiCd), less than 5% self-discharge rate (3 to 6 times less than others), high nominal cell voltage (up to 3 times more than NiCd), and other characteristics. On the other hand, Li-ion batteries are the most expensive ones on the market. Despite their cost, they are used on a daily basis in home electronics, portable electronic devices, or EVs.

The most common lithium based batteries are: lithium cobalt oxide, with high specific energy but only moderate performance, specific power, safety, and life span (used for mobiles, laptops, cameras); lithium manganese oxide, with better performance in specific power, safety, and life span (used for power tools and medical device); and lithium nickel manganese cobalt oxide, the preferred candidate for the electric vehicles as it has the lowest self-heating rate (Cadex Electronics Inc., 2017).

In the actual context of climate change threats, lithium batteries fulfil lot of expectations in order to achieve a cleaner and more sustainable solution for transports, embodied by EVs. Thus, lithium shortages could end by threaten the EVs market supply (Grosjean, Herrera Miranda, Perrin, & Poggi, 2012). Moreover, undersupply can be expected until 2045 in the European Union according to a system dynamics analysis developed by Miedema & Moll (2013). Ziemann, Weil, & Schebek (2012) identified a high potential of supply disruption for this element, and Sverdrup (2016) also identified a noticeable discrepancy between consumption and production.

This paper focuses in first place in analysing lithium prices and their expected evolution. In second place it studies in deep five ready-to-go lithium mining investment projects worldwide: Whabouchi Project in Canada, Keliber Project in Finland, Cauchari-Olaroz Salars Project in Argentina, Sonora Project in Mexico, and Pilgangoora Project in Australia. The main purpose being to provide an exhaustive analysis of lithium mining investment in order to facilitate the development of preliminary economic assessments of future lithium mining projects, fighting again supply disruption and accelerating the transition to sustainable energy.

Ensuring lithium supply for the growth of energy-sustainable industrialised countries is crucial, and different approaches should be undertaken (Ziemann et al., 2012). Apart from the path of accelerating new mines, recycling should also provide significant secondary supply, as in the case of other critical raw material like rare earths (Habib & Wenzel, 2014). Resuming: for the purpose of technological transition, time matters (Kushnir & Sandén, 2012).

2. LITHIUM PRICES

Lithium industry distinguishes three types of lithium carbonate according to quality: battery-grade, with purity ranging at 99.5–99.8%, low mineral impurities and water content less than 0.5%, used for manufacturing of high energy end battery material; technical-grade, with purity around 99.0–99.3% and water content less than 0.7%, used for industrial applications such a ceramics or lubricants; and industrial grade, with purity around 99.0%, used as a low-cost alternative to technical grade lithium carbonate.

Global lithium market is usually measured in terms of lithium carbonate equivalents (LCE), given that lithium carbonate is the most commonly traded product in the market due to the compound’s application in a wide range of end uses. As lithium carbonate contains around a 18.8% of Li, Li can be converted into LCE by using the following pattern:

$$Mass\ of\ LCE = 5.323\ x\ Mass\ of\ lithium\ metal.$$

Lithium is usually quoted by independent media organisations: lithium carbonate min. 99.5% Li_2CO_3 battery-grade, spot prices range, ex-works domestic China, yuan per tonne (Yn/t) and lithium carbonate min. 99.5% Li_2CO_3 battery-grade, spot prices CIF China, Japan and Korea, $/kg. Other usually quoted compounds are: lithium cobalt oxide min 60% Co ex-works China (Yn/kg); Lithium hydroxide min 56.5% $LiOH.H_2O$ battery grade, spot price range, ex-works domestic China (Yn/t); and lithium hydroxide monohydrate min 56.5% $LiOH.H_2O$ battery grade, spot prices CIF China, Japan and Korea, $/kg (Argus Media Ltd, 2016; Fast Markets MB, 2018). Due to its continuous growth, Maxwell

(2015) saw inevitable the trading of lithium in a major metal exchange. Nowadays, London Metal Exchange (LME) is considering to start with lithium contracts to tap electric car boom.

Till the last decade of the XXth century, lithium prices were negotiated by bilateral contracts between producers and consumers. After that, the appearance of a major producer, Sociedad Química y Minera de Chile, S.A. (SQM), led to a difficult situation to obtain price information. From 2010, the entry of new producers was associated with a growing transparency in prices (Maxwell, 2015). Nevertheless, and until lithium will be traded in a stock exchange, price information availability will still depend on private price and market data providers, with all the inconveniences and uncertainties that this question arises, starting from the most important one (from at least a scientific point of view): the need to pay for these data.

Figure 1 presents Lithium Carbonate min. 99.5% Li_2CO_3 battery-grade, spot prices CIF China, Japan and Korea ($/t), from the first semester of 2002 till March, 2019. Information from different market data providers, such as Fast Markets MB, Argus Media Ltd., Trading Economics, etc., was gathered in order to allow the construction of this figure.

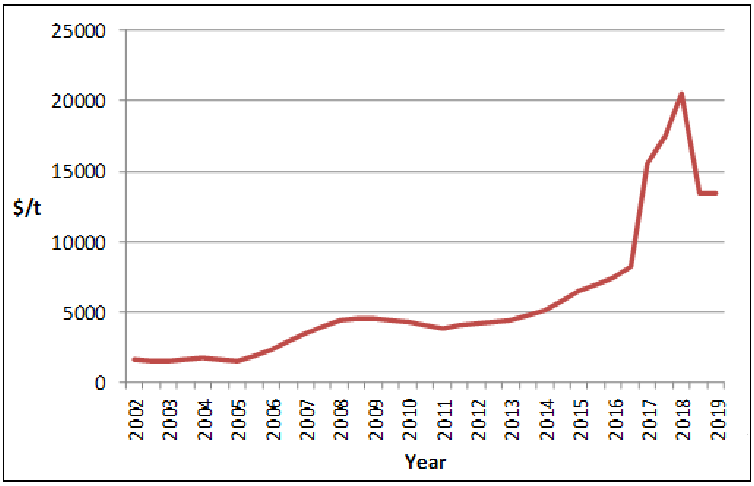

Figure 1. Lithium Carbonate min. 99.5% Li_2CO_3 battery-grade, spot prices CIF China, Japan and Korea ($/t), from the first semester of 2002 till March, 2019. Source: different market data providers

An analysis of the lithium market may give some clues about which could be the future behaviour of prices.

According to its global supply, demand and prices, Martin et al. (2017) stated that lithium demand, that is caused mainly by electric mobility and driven in many cases by governmental policies, will increase between a 6% and a 9% in 2020. Moreover, a strong increase of future lithium demand is expected unanimously (Grosjean et al., 2012; Mohr, Mudd, & Giurco, 2012; Habib et al., 2014; McCormick, 2016; Sverdrup, 2016; etc.).

Despite this forecasted increase in the demand, prices of lithium in China have been almost cut by the half during 2018. According to Benchmark Mineral Intelligence (BMI), it was caused by a pulling back of subsidies in China's electric vehicles, a ramping up of the production by miners and the fact that consumers destocked their supplies, holding back on purchases.

With this situation in mind, lithium market behaviour can be compared with the evolution of the dysprosium oxide market. This rare earth oxide (REO) is very important for the permanent magnet industry, dominating the increasing demand of high-efficiency traction motors that are used in hybrid and electric vehicles, wind turbine generators and hard disc drives. In 2011 prices of dysprosium oxides spiked after a cut of Chinese exports (China's share of the market was around the 90%) but due to the development of numerous mining projects all around the world and despite stockpile purchases by the US Defense Logistics Agency and the China's State Reserve Bureau during 2013 and 2014 (Argus Media Ltd., 2014), prices came back to a normal situation (Riesgo García, Krzemień, Manzanedo del Campo, Menéndez Álvarez, & Gent, 2017). Supporting this fact, Fernández (2017) stated that the high price volatility of rare earth oxides during 2011-2012 had a very limited impact when analysing the systematic risk of rare earth elements (REE) companies during that period, thus the market expected this return to normality.

Figure 2 presents the evolution of dysprosium oxide prices from 2001 till 2016 in Europe. After the spike happened during 2011 and 2012, prices came back to the "normal" trend (below the stripped line) previous to the spurious phenomenon: under 500 $/kg.

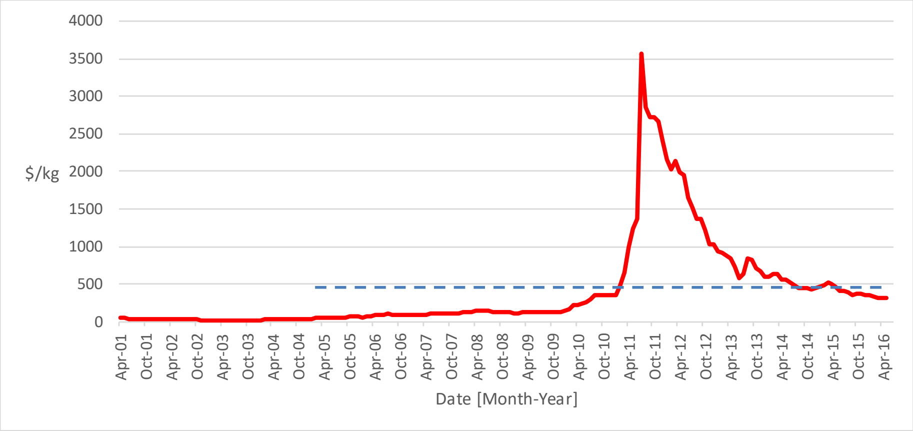

Figure 2. Dysprosium oxide prices in Europe from 2001 until 2016. Source: Riesgo García, Krzemień, Manzanedo del Campo, Escanciano García-Miranda, & Sánchez Lasheras (2018) (Adapted from MetaErden GmbH)

Mohr et al. (2012) claimed that there are sufficient lithium recoverable resources in order to ensure the demand of future electric vehicles, and that the recycling of lithium batteries will represent a significant lithium supply in the future. Moreover, Kesler et al. (2012) stated that lithium resources can be estimated in more than 31 Mt, something that will cover the demand for many decades considering that 2016 production was around 35 kt. Thereby, and taking into account how dysprosium oxide prices have evolved in the past, a similar behaviour of lithium prices could be expected, mainly based on the development of lithium mining projects worldwide and on the return to an offer and demand equilibrium with prices fixed by mining costs with normal mining market margins.

According to these approaches, Figure 3 shows quite a probable upper limit for the next future: 10,000 $/t. This figure can only be considered as a conservative upper value for addressing specifically financial analyses of lithium mining investment projects.

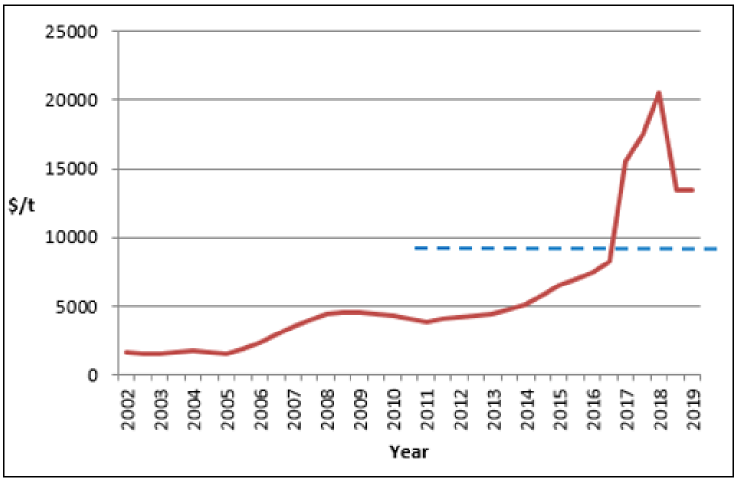

Figure 3. Forecasted upper limit (stripped line) for future Lithium Carbonate min. 99.5% Li_2CO_3 battery-grade, spot prices CIF China, Japan and Korea ($/t)

On the other hand, the only reliable alternative to analyse LCE prices and their expected evolution is to undergo a time series analysis like the one described by Krzemień, Riesgo Fernández, Suárez Sánchez, & Sánchez Lasheras (2015) as due to the little amount of data available, the use of other tools of artificial intelligence will be compromised when trying to achieve reliable mid-term forecasts. @RISK 7.5 (Palisade Corporation, New York) is the software used for this simulation.

Both the mean and the variance of the data set were non-stationary, so the following transformations were considered: (1) a logarithmic transformation to achieve variance stationarity and (2) a first-order differencing detrend to achieve mean stationarity. Moreover, a seasonal adjustment with a first order differencing over an annual period was applied in order to achieve a more consistent time series representation, as in Matyjaszek, Riesgo Fernández, Krzemień, Wodarski, & Fidalgo Valverde (2019).

Based on the autocorrelation function (ACF) and the partial autocorrelation function (PACF) plots, a first order moving average MA (1) should be the model that best fits the data set, something that was confirmed by both the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). Figure 4 presents the forecasted prices till 2022 that were obtained.

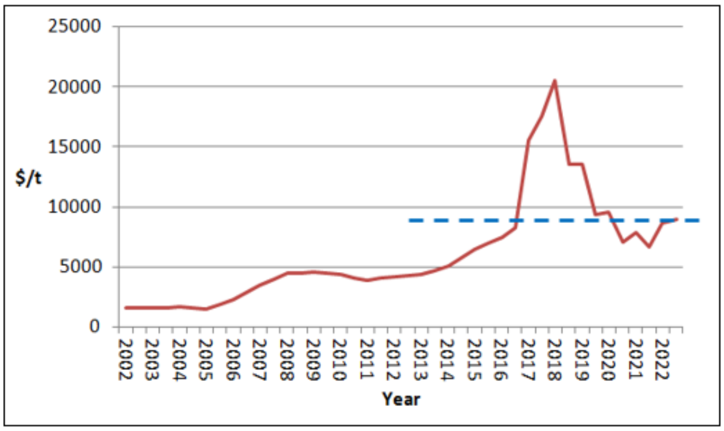

Figure 4. Forecasted prices for Lithium Carbonate min. 99.5% Li_2CO_3 battery-grade, spot prices CIF China, Japan and Korea ($/t)

It is then possible to conclude that LCE prices are expected to return to a more stable behaviour (below 10,000 $/t) despite the increasing demand, mainly based on: (1) a ramping up of the production by miners, (2) the return to an offer and demand equilibrium with prices fixed by mining costs with normal mining market margins, and (3) the fact that there are sufficient lithium recoverable resources in order to ensure the demand of future electric vehicles. Moreover, recycling of lithium batteries will represent a significant supply for the future.

Also in line with this conclusion, Gil-Alana & Monge (2019) stated that in the case of negative shocks that may affect lithium global production, the series will probably return to the original trend by itself, but in the case of a ramping up of the production (a positive shock) it occurs the contrary and special attention should be paid in order to make that change permanent. Something similar happened when rare earth prices dramatically spiked. The world's reaction to this fact was the development of many rare earth mining projects outside China, many of whom failed when prices fell again, although several of them survived (Riesgo García et al., 2017).

3. WHABOUCHI PROJECT (CANADA)

Nemaska Lithium Inc. is a Canadian based lithium company listed on the Toronto Stock Exchange (TSX:NMX), Frankfurt Stock Exchange (FRA:N0T), as well as in the OTC Markets group (OTCXQ:NMKEF), an American financial marketplace of over-the-counter securities (to be traded on this market companies must undergo review and comply with specific requirements).

Nemaska Lithium’s key project is Whabouchi mine, located in Eeyou Istchee, James Bay Region of Quebec, Canada.

The Whabouchi mineralisation is found in spodumene-bearing pegmatite dyke complexes and hosted in an amphibolized meta-basalt. It is approximately 1.3 km in length by 130 m wide, with a depth reaching at least 300 m below the surface. The lithium is located almost exclusively in the spodumene.

The average content of spodumene in the Whabouchi deposit represents 20% in volume. Another lithium-containing mineral, petalite, can be observed, and represents less than 2% in average.

The Whabouchi project life of mine (LOM) is 26 years. The mine will combine opencast and underground methods of mining. Opencast mining activities will be conducted by conventional drilling & blasting and related operations for the first 20 years. It will be followed by underground mining method of longhole stopping with crown pillars and ramp access, for the remaining 6 years.

The project's capital expenditures (capex) are estimated in 455.9 M$, completed to an estimated level of accuracy of ± 15%, and including a working capital equal to three (3) months operating costs. Provision for sustaining capital is 184.1 M$ but it is not included in the capex. The mine production rate will be 1 Mtpa of ore during the opencast operation, with a stripping ratio of 2.2:1, and 1.2 Mtpa of ore during underground operation, making an average of 1.05 Mtpa.

Capital costs are shown in Table 1, with a considered exchange rate of 0.80 USD/CAD.

Table 1. Whabouchi project capital expenditures (Met-Chem, 2016)

Item	Cost (M$)
Mine and Concentrator	
Direct costs	120
Mine Development Pre-Stripping	3
Trust Fund Rehabilitation First Payment	3
Indirect Costs (incl. Owner´s Cost)	47.8
Contingencies	17.4
Subtotal Mine and Concentrator	**191.2**
Hydromet Plant	
Total Direct Costs	184.2
Total Indirect Costs	36,5
Contingencies	27.6
Subtotal Plant	**248.3**
Working Capital	16.4
Total Capital Cost	**455.9**

The reserves statement presented in Table 2 refers to the Canadian standards for public disclosure (NI 43-101, 2011). Mineral reserves were estimated based on an underground cut-off grade of 0.80 % Li_2O, and for the open pit mine of 0.43 % Li_2O. Mining dilution was estimated at 10%.

Table 2. Whabouchi project mineral reserves (Met-Chem, 2016)

Category	Tonnage (Mt)	Li_2O grade (%)
Proven	13,3	1,54
Probable	14,0	1,39

Total	27,3	1,46

The average FOB selling prices used were 9,500 $/t lithium hydroxide monohydrate (LiOH-H_2O), with an 88.1% of Li, and 7,000 $/t lithium carbonate ($Li_2CO_3$), with a 11.9% of Li.

Life of mine cash operating costs are 184.94 $/t of spodumene concentrate, estimated with a precision of ± 15%. Table 3 presents the operating costs in $ per tonne of ore. Operating cost per tonne of Li_2CO_3 are 2,785 $/t.

Table 3. Whabouchi project operating expenses (OPEX). (Met-Chem, 2016)

ITEM	$/t of ore
Mining	11.43
Concentrator	26.36
Hydromet plant	27.50
Transport	8.17
TOTAL COST	**73.46**

The ore will be transported to Whabouchi by trucks, where the concentrator plant will be located, and the concentrate will be transported by train to the hydrometallurgical Plant at Shawinigan.

The concentrator will include crushing, dense media separation, grinding, flotation and magnetic separation. Before leaving the concentrator plant, the concentrate will undergo further steps of filtration, drying and material handling, including storage and loading of dried spodumene concentrate on road trucks. The production will be 216,485 dry tonnes of 6.0% Li_2O spodumene concentrate, with more than 77% of lithium recovery.

After, the spodumene concentrate will be processed into lithium carbonate and lithium hydroxide at the processing hydromet plant located in Shawinigan. The hydromet plant will be designed to produce a nominal 27,645 tpa of lithium hydroxide monohydrate crystals, and a nominal 3,245 tpa of lithium carbonate powder. The overall lithium recovery will be 86.5 %. Table 4 presents the amounts mined and processed per year by the project.

Table 4. Whabouchi project processing figures. (Met-Chem, 2016)

Phase	ktpa	kt total
Open pit mining (20 years)	3 200	64 000
Underground mining (6 years)	1 200	7 200
Mining	2 738	71 200
Processing	1 046	27 196
Lithium hydroxide monohydrate (57.5%)	27.64	718.77
Lithium carbonate (99.9%)	3.27	84.94

4. KELIBER PROJECT (FINLAND)

Keliber Oy is a Finnish junior mining company and does not have another active project, with an objective of producing high-purity lithium carbonate, especially for the needs of the international lithium battery market. The company is 75% owned by Finnish private investors, and the remaining 25% is held by Norwegian Nordic Mining ASA.

It´s lithium project consists of four lithium deposits in the province of Central Ostrobothnia, Finland: Syvajarvi, Lantta, Rapasaari, and Outovesi. Keliber Oy aims with this project to produce 90% battery grade lithium carbonate (min. 99.5% Li_2CO_3), and 10% high-purity lithium carbonate (min. 99.9% Li_2CO_3) from spodumene pegmatite ore.

The project LOM will be 16.2 years and will use a conventional open-pit mining with drilling, blasting, loading, and hauling operations. The mineralization is found in pegmatite veins which are either subvertical or flat lying.

The capex prevision of 180.39 M$ was completed with an accuracy of ±30%, and is presented in Table 5. It has been calculated for a production of 280,000 tpa of ore, and 6,000 tpa of lithium carbonate. The average stripping ratio is 5.9:1 throughout the LOM. The exchange rate used was 1.0886 EUR:USD.

Table 5. Keliber project capital expenditures (Sweco Industry Oy, 2016)

Item	M$
Mining	18.51
Plant project management and engineering	17.85
Area and infrastructure	41.15
Crushing and concentrating	21.88
Leaching process	45.29
Common process investments	12.30
Laboratory and facilities	4.25
Test runs and start-up	1.74

Elevation of tailing dams	13.28
Rehabilitation	4.14
TOTAL	**180.39**

Ore reserves estimate of Keliber project deposits has been reported using the JORC Code (2012), with a Li_2O cut-off grade of 0.5%. Ore loss of 5% and waste rock dilution of 15% are anticipated. Mineral reserves are shown in Table 6.

Table 6. Keliber project mineral reserves (Sweco Industry Oy, 2016)

	Proven and Probable (kt)	Li_2O grade (%)
Syvajarvi	1,480	1,19
Rapasaari	1,750	1,09
Lantta	101	0,93
Outovesi	250	1,2
Total	**4,490**	**1,11**

Expected lithium carbonate selling price is 8,600 $/t.

Operating expenses estimated with accuracy of ±30% are presented in Table 7, showing operating cost per tonne of ore. Operating cost per tonne of Li_2CO_3 are 4,266 $/t.

Table 7. Keliber project operating expenses (Sweco Industry Oy, 2016)

Item	$/t of ore
Mining	38.27
Processing	54.81
TOTAL	**93.08**

Processing of the extracted ore will take place in a lithium carbonate plant located nearby the site. Lithium carbonate will be produced from a spodumene flotation concentrate (containing 4.5 % of Li_2O with average moisture of 8-10%) by a pressure leach process with a flotation recovery of 80%. The spodumene concentrator and lithium carbonate production plant will be located at Kalavesi site, that will be used as a central processing facility for the surrounding lithium deposits. Leaching recovery is estimated at 90%. Table 8 presents the amounts processed by the project.

Table 8. Keliber project process design criteria (Sweco Industry Oy, 2016)

Phase	ktpa	kt total
Mining	1 919	31,088
Processing	275	4,455
Lithium Carbonate	6	97.2

5. CAUCHARI-OLAROZ SALARS PROJECT (ARGENTINA)

Lithium Americas is a company listed on the Toronto stock Exchange (TSX:LAC), and in the OTC Markets group (OTCXQ:LACDF). It is currently developing, through a Joint Venture with Sociedad Química y Minera de Chile, a brine lithium project located in Jujuy, Argentina. Through its subsidiary Lithium Nevada Corp., Lithium Americas is also operating another Lithium project in northern Nevada. With these two main projects Lithium Americas intends to become one of the biggest players in the lithium market for energy storage and electric vehicles.

The Cauchari-Olaroz project is the biggest ready-to-go lithium project, and the third largest lithium brine project in the world. Both salars are located approximately 250 km northwest of San Salvador de Jujuy, with an average elevation close to 4,000 m.a.s.l.

The LOM of the project has been calculated up to 40 years. As it is a brine deposit (lithium is dissolved in groundwater), a series of wells (wellfield) will be used for pumping off lithium containing waters. The brines are saturated in sodium chloride with total dissolved solids (TDS) of around 27% (324 to 335 g/l), and an average density of about 1.215 g/cm^3. The other primary components of these brines include: potassium, lithium, magnesium, calcium, sulphate, HCO_3, and boron as borates and free H_3BO_3. Since the brine is saturated in NaCl, halite is expected to precipitate during evaporation.

A Production of 10.09 Mm^3 of brine per year is expected, with a predicted average of lithium concentration of 698 mg/l, in order to produce 25,000 tpa of lithium carbonate. The estimated capex is 425 M$ which is presented in Table 9, with an accuracy of ± 15%, and contingency of 15%. The exchange rate used between the Argentine peso and the US dollar was 15.90 ARD:USD.

Table 9. Cauchari-Olaroz salars project capital expenditures (Lithium Americas, 2017)

CAPEX	**M$**
Brine extraction wells	18.91
Evaporation ponds	164.77
Lithium Carbonate Plant	188.61
Infrastructure & general	52.71
TOTAL CAPEX	**425.00**

Using a lithium cut-off grade of 354 mg/l, which represents a brine processing constraint, mineral reserve estimation of the project according to NI 43-101 (2011) is presented in Table 10. According to Waldie & Whyte (2012), NI 43-101 (2011) also addresses mineral projects that are hosted in brine, as concerning the instrument application what is relevant is the form of the mineral and not the type of medium from which the mineral is extracted.

Table 10. Cauchari-Olaroz salars project reserves (Lithium Americas, 2017)

	Li_2CO_3 (kt)	Average concentration (mg/l Li)
Proven	187	712
Probable	1,312	695
TOTAL	**1,499**	**698**

Key financial outcomes are presented in Table 13, calculated with a lithium Carbonate selling price of 12,000 $/t.

For an estimated production of 25,000 tpa of lithium carbonate, the operating expenses (opex) will be 62.3 $M per year, calculated with an accuracy of ±15%. Table 11 presents operating costs per m^3 of brine. Operating cost per tonne of Li_2CO_3 are 2,495 $/t.

Table 11. Cauchari-Olaroz salars project operating expenses (Lithium Americas, 2017)

ITEM	$/$m^3$ of brine	$/t of brine
Reagents	2.45	2.02
Maintenance	0.52	0.43
Pond harvesting	0.85	0.70
Product transport	0.33	0.27
Others	2.01	1.65
TOTAL	**6.16**	**5.07**

Production process to obtain lithium carbonate has several steps. Firstly, the brine is extracted through the borehole field in the salars. In second place, processing will use solar evaporation ponds allowing the removal of sulphates and other unwanted salt. Then lime is added to remove magnesium and most of the sulphates. After another concentration stage at the corresponding ponds, the concentrated lithium-rich brine is fed to the lithium carbonate plan. The initial stage at the lithium carbonate plant is where boron is extracted through an organic solvent extraction process. Afterwards, the brine goes into two carbonation stages with sodium carbonate, after which lithium carbonate is obtained.

An amount of 403.78 m^3 of brine is required to obtain 1 t of Li_2CO_3. Volumes processed by the project are shown in Table 12.

Table 12. Cauchari-Olaroz salars project processing figures (Lithium Americas, 2017)

ITEM	per year	total
Brine from wells (Mm^3)	10.1	403.8
Produced Li_2CO_3 (ktpa)	25	1,000

6. SONORA PROJECT (MEXICO)

The majority of the Sonora lithium project is owned in a 70% by Bacanora Minerals Ltd, an AIM and TSX listed company focused on becoming a large scale producer of battery grade lithium carbonate (AIM:BCN; TSXV:BCN), in Joint Venture with Rare Earth Minerals, who owns a 30%. Sonora Project is located in the Sonoran Desert in the Mexican state of Sonora close to Bacadéhuachi, located approximately 170 km south of US – Mexican border.

Lithium mineralisation of Sonora project consist in series of lithium-bearing clays occurring in two bedded sequences separated by an ignimbrite sheet. Mineralised intervals within the clay units vary for the upper clay unit from 25% to 80% of the overall thickness, and from 40% to 100% for the lower clay unit.

LOM was calculated over 20 years with additional resources and reserves to extend operations beyond. Mining will be conducted by an open-pit truck and shovel mining method using hydraulic excavators, haul trucks, and other auxiliary machinery. The open pit design is based on 10 m mining benches, 25 m wide haul roads and 42-degree inter-ramp slope angle on the hanging wall side of the pits. Project was calculated with two stages of production. During the first 2 years, production should reach 17,500 tpa of Li_2CO_3. In the second stage of the remaining 18 years of production, it will increase up to 35,000 tpa. Besides, the project will also produce up to 50,000 tpa of potassium sulphate (K_2SO_4) as a by-product.

Capital costs of 528.1 M$ were estimated with an accuracy of ± 25%. A mining design ratio of 3:1 was calculated for the entire LOM, with a production of 2.8 Mtpa of ore. Capital costs are presented in table 13. Sustaining capital costs were considered in this case, as they comprise the built up of the mining fleet according to the expected mining rate, together with processing capital requirements. Therefore, they cannot be considered as “normal” sustaining capital costs.

Table 13. Sonora project capital expenditures (Ausenco Engineering Canada Inc., 2016)

Description	**Cost M$**
Mining Equipment	28.6
Mining Infrastructure	3.7
Beneficiation plant	38.6
Processing Plant	171.9
On-site Infrastructure	25.5
Off-site Infrastructure	22.7
EPCM/Owner´s costs/Indirect	75.6
Sustaining capital costs	111.0
Contingency	50.5
TOTAL	**528.1**

Mineral reserve estimation used a cut-off grade of 1,200 ppm of Li, an ore recovery factor of 100% and a mining dilution rate of 10%. Results are reported according to NI 43-101 (2011), and are presented in Table 14.

Table 14. Sonora project mineral reserves (Ausenco Engineering Canada Inc., 2016)

	Clay tonnes (Mt)	Li (ppm)	LCE (kt)
Probable	129.7	3,015	2,083

A flat rate price of 6,000 $/t of battery-grade Li_2CO_3, and 600 $/t of commercial grade K_2SO_4 had been assumed over the LOM.

Operating costs of the project are 35.97 $/t of ore and were estimated with an accuracy of ± 25%, and are presented in Table 15. The estimate includes all site-related operations to the product. Operating cost per tonne of Li_2CO_3 are 2,698 $/t.

Table 15. Sonora project operating expenses (Ausenco Engineering Canada Inc., 2016)

ITEM	$/t of ore
Mining	7.93
Processing	25.56
General and Administration	2.48
TOTAL COST	**35.97**

A summary of the recovery method is: beneficiation to recover lithium while rejecting gangue (calcite and silica) using scrubbing, hydrocyclone classification and reverse flotation; gypsum roasting; and a hydrometallurgical process. Overall recovery of the Sonora lithium plant is predicted to be 69.8% of lithium, and 57.2% of potassium. Table 16 shows the amounts mined and processed throughout the life of mine.

Table 16. Sonora project processing figures (Ausenco Engineering Canada Inc., 2016)

	ktpa	kt total
Mining	10,456.65	209,133
Processing	2,603	52,060
Produced Li_2CO_3	33.25	665
Produced K_2SO_4	49.5	990

7. PILGANGOORA PROJECT (AUSTRALIA)

Altura Mining Ltd, listed on the Australian Securities Exchange (ASX:AJM), is a developer of lithium concentrates. The company completely owns the Pilgangoora project which is situated in Western Australia, not far for town of Port Hedland. Project aims to produce approximately 219 ktpa of spodumene concentrate, containing 6% of Li_2O which will be later shipped to lithium producers mainly in China. The project is expected to start in 2018.

Pilgangoora mineralisation is found in clear pegmatite dykes hosted within amphiboles in a range of thickness from 5 to 40 m. Mining will be carried out by conventional bulk mining method with the use of individual mechanization and blasting operations. Operations are going to take place in one pit with dimensions of 1,500 m length, up to 500 m width, and 200 m depth.

Estimated volume of production should be achieved by mining and processing of 1.54 Mtpa of lithium oxide containing ore. Project LOM is based on current mineral reserve estimation and expected to be 13.2 years. Average stripping ratio throughout the life of mine is 2.9:1.

Capital costs of 98.27 M$ without a sustaining capital of 5.73 M$ are estimated with an accuracy of ±10%, in order to reach a production of 219 ktpa. Exchange rate used was 0.75 AUD:USD. Capital costs are presented in Table 17.

Table 17. Pilgangoora project capital expenditures (Altura Mining Limited, 2017)

Item	Cost (M$)
Site Establishment	0.09
Mine Development	8.92
Process Plant Equipment	66.83
Process Plant Support facilities	0.37
Non Process Infrastructure	6.56
Road and Rail Crossing Upgrades, Camp	8.79
Owners Cost	7.5
TOTAL	**98.27**

Mineral reserves were estimated based on a cut-off grade of 0,43% Li_2O using the JORC Code (2012) for reporting of the results. Ore losses of 5%, and dilution of 0% is expected. Mineral reserves of Pilgangoora project are presented in Table 18.

Table 18. Pilgangoora project mineral reserves (Altura Mining Limited, 2017)

Category	Ore Mt	Li_2O (%)	Contained Li_2O (kt)
Proven	8.1	1.14	92
Probable	26.1	1.01	265
TOTAL	**34.2**	**1.04**	**357**

A selling price of 538.8 $/t of wet tonne of spodumene at 6% Li_2O has been assumed for calculations.

LOM operating expenses are estimated also with an accuracy of ±10% at 33.73 $/t of ore, and are shown in Table 19.

Table 19. Pilgangoora project operating expences (Altura Mining Limited, 2017)

Item	$/t of ore

Mining	10.38
Processing	13.74
Haulage and Port	4.13
Others	5.48
TOTAL	**33.73**

Ore processing will be conducted by conventional four-stage crushing and screening, reflux classifying, followed by dense medium separation and flotation at concentrator. A recovery of 83 % of Li_2O is expected throughout the process. After it is processed, the final product will be transported to Port Hedland from where it will be shipped on bulk carrier vessels. Table 20 shows Pilgangoora project processing figures.

Table 20. Pilgangoora project processing figures (Altura Mining Limited, 2017)

Phase	**Ktpa**	**Kt total**
Mining	6,006	79,279.2
Processing	1,540	20,328
Produced Li_2O (6%)	219	2,890.8

8. DISCUSSION

The economic aspects of the different lithium mining investment projects will be analysed in this section. The main aim being to provide a useful tool for investors and mining project developers by specifying an “order of magnitude” of lithium mining investments, and facilitating the development of preliminary economic assessments according to the NI 43-101 (2011). The methodology will be the one used by Matyjaszek, Wodarski, Krzemień, Escanciano García-Miranda, & Suárez Sánchez (2018) addressing coking coal mining projects, especially in the way that operating expenses are analysed. Quite similar approaches were developed by Suárez Sánchez et al. (2015) addressing tungsten mining projects, and by Riesgo García, Krzemień, Manzanedo del Campo, Menéndez Álvarez & Gent (2017) addressing rare earth mining projects.

8.1. Cut-off grades

For the JORC Code (2012), the cut-off grade of a given mineralisation is the lowest grade/quality that allows it to be qualified as economically mineable. It can be defined twofold: by economic evaluation or by its physical/chemical attributes. On the other hand, the PERC Reporting Standard (2017) defines it on an economic block value basis rather than on the grade/quality.

Figure 5 presents the cut-off and mineral reserve grades of the different project but Cauchari-Olaroz.

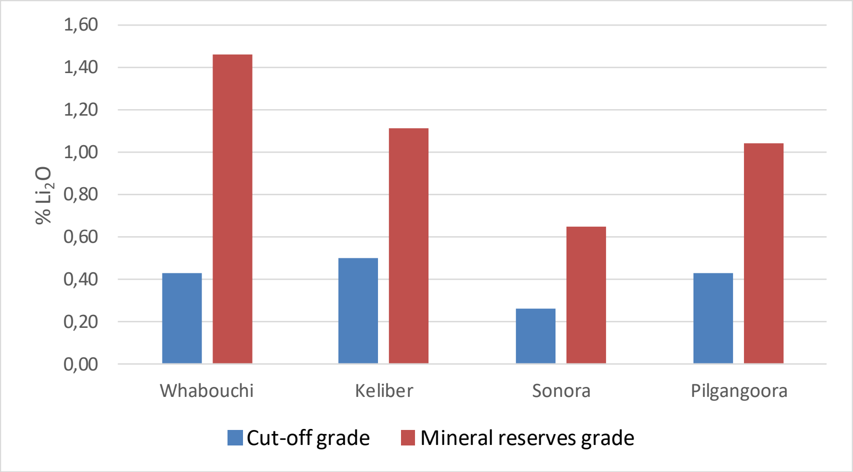

Figure 5. Cut-off and mineral reserves grades

Cut-off grades in the case of lithium-bearing hard rocks are in a range of 0.43-0.50% of Li_2O, being approximately the half (0.26%) for the analysed case of lithium-bearing clays (Sonora). For Whabouchi, the cut-off grade figure corresponds to the open pit mine (20 years). For the underground mine (remaining 6 years) the cut-off grade is 0.80%. Cauchari-Olaroz salars use a cut-off grade of 354 mg/l Li, and the mineral reserves grade is 698 mg/l Li.

8.2. Dilution and extraction ratios

Table 21 presents the deposit types and their dilution and extraction ratios.

Table 21. Dilution and extraction ratios of the analysed projects

Project	Deposit type	Dilution	Extraction ratio
Whabouchi	Dyke	10%	-
Keliber	Subvertical or flat veins	15%	95%
Sonora	Bedded sequences	10%	100%
Pilgangoora	Dykes	0%	95%

Thus, an average 12% of dilution for subvertical or flat sequences and a 5% for dykes can be considered as appropriate for the development of preliminary economic assessments of future lithium mining projects. On the other hand, a 97% for the extraction ratio seems to be quite a representative figure for the same purpose.

8.3. Metallurgical recoveries

Table 22 shows the metallurgical recoveries of the different projects.

Table 22. Metallurgical recoveries of the analysed projects

Project	Recovery in Li_2O	Recovery in Li_2CO_3
Whabouchi	77%	86.5%

Keliber	80%	90%
Cauchari-Olaroz	-	-
Sonora	69.8% (overall)	
Pilgangoora	83%	-

Based on these figures it is possible again to establish general assumptions for the recoveries in order to develop a preliminary economic assessment: 80% of Li recovery in Li_2O, and 88% recovery in Li_2CO_3. The overall recovery can be established in a 70%.

8.4. Capital expenditures (capex)

Trying to estimate the capex of a generic lithium mining project, it was possible to establish a relation between the Li_2CO_3 production in ktpa and the capex in M$. Pilgangoora project was not considered as it will only produce Li_2O. On the other hand, Whabouchi production of lithium hydroxide monohydrate (57.5%) was transformed to Li_2CO_3 applying the conversion factor of 0.88, but without considering the different purity of the products.

Figure 6 presents a scatterplot of the different projects, with a 99.99% value of R^2 obtained in the regression model.

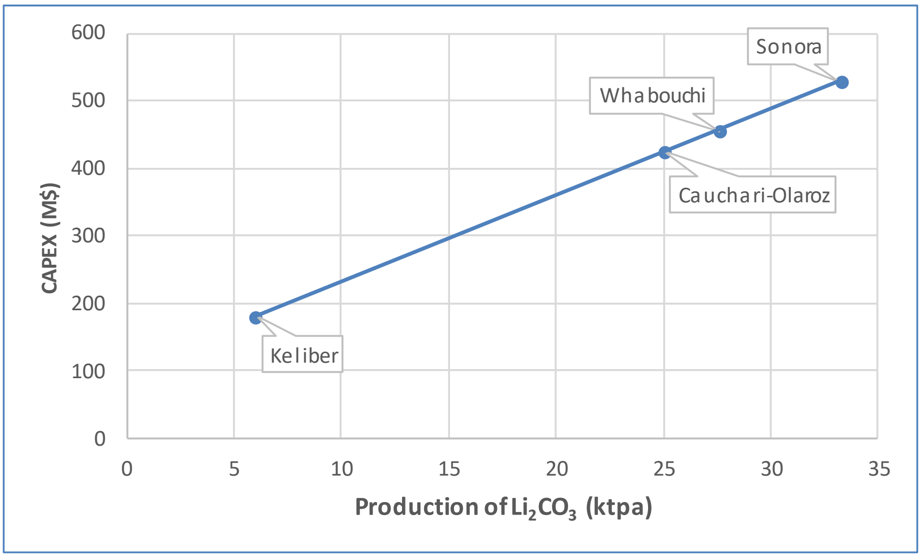

Figure 6. Li_2CO_3 production in ktpa versus capex in M$

Therefore, the relation between the variables for a generic lithium mining project could be:

$$Capex\ (M\$) = 12.77 \times Production\ of\ Li_2CO_3\ (ktpa) + 104.13$$

8.5. Operating expenses (opex)

Operating expenses are presented in Figure 7 in $/t of ore. As costs of Cauchari-Olaroz are estimated in $/t of brine or $/m3 of brine, they cannot be compared with the rest of the projects. On the other hand, Pilgangoora processing costs only include the obtention of spodumene at 6% Li_2O.

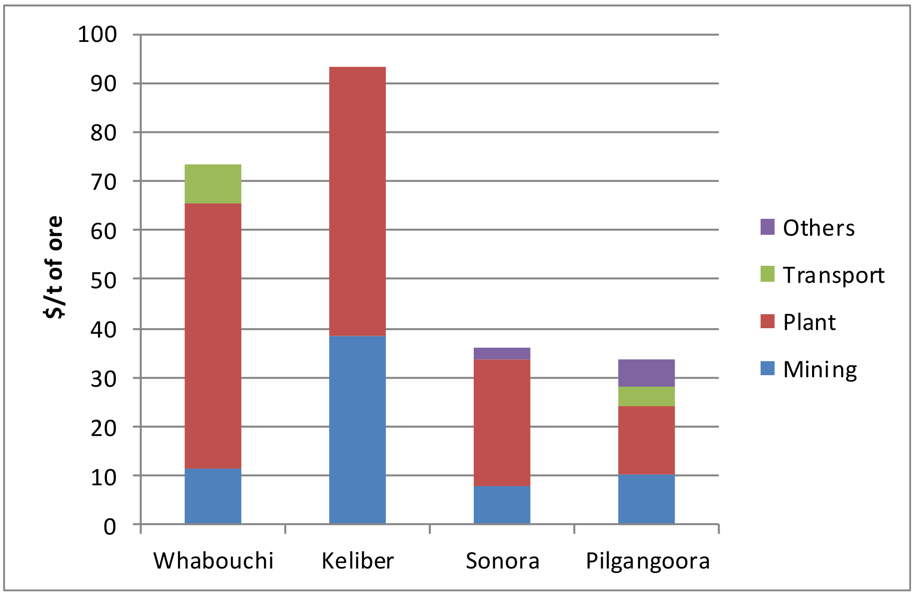

Figure 7. Operating costs in $/t of ore

Mining costs can be quite well related with the stripping ratio of the mines:

a) *Mining costs #1*: 11.43 $/t of ore for a stripping ratio of 2.2 (Whabouchi), as in the case of Pilgangoora, even with a bigger stripping ratio the costs are lower so the most unfavourable value was selected.
b) *Mining costs #2*: 38 $/t of ore for a stripping ratio of 5.9 (Keliber).

In the case of Sonora, although with a stripping ratio of 3, it presents lower mining costs (7.93 $/t of ore) than Whabouchi and Pilgangoora. This fact can be justified based on the specific kind of mineralisation, consisting in series of lithium-bearing clays occurring in two bedded sequences separated by an ignimbrite sheet. In Whabouchi, Pilgangoora, and Keliber, lithium occurs in hard-rocks.

Little can be said about processing costs. Whabouchi produces mainly lithium hydroxide monohydrate from a mineral with 1.46% of Li_2O. Keliber produces lithium carbonate from a mineral with 1.11% of Li_2O. Both costs are around 54.3 $/t of ore, but this figure can be only considered as orientative for a generic lithium mining investment. On the other hand, Sonora processing costs, that will produce lithium carbonate and potassium sulphate from lithium-bearing clays with a 0,26% of Li_2O, are 25.56 $/t of ore, almost the half than in the case of lithium from igneous rocks.

Due to the very different lithium-bearing deposits, a comparison among the costs in $/t of Li_2CO_3 should be addressed in order to determine whether lithium retrieved from hard-rocks, clays, or salars, could represent a push out of the market for the rest of them. Figure 8 presents the operating costs in $/t of Li_2CO_3 of the different projects but Pilgangoora.

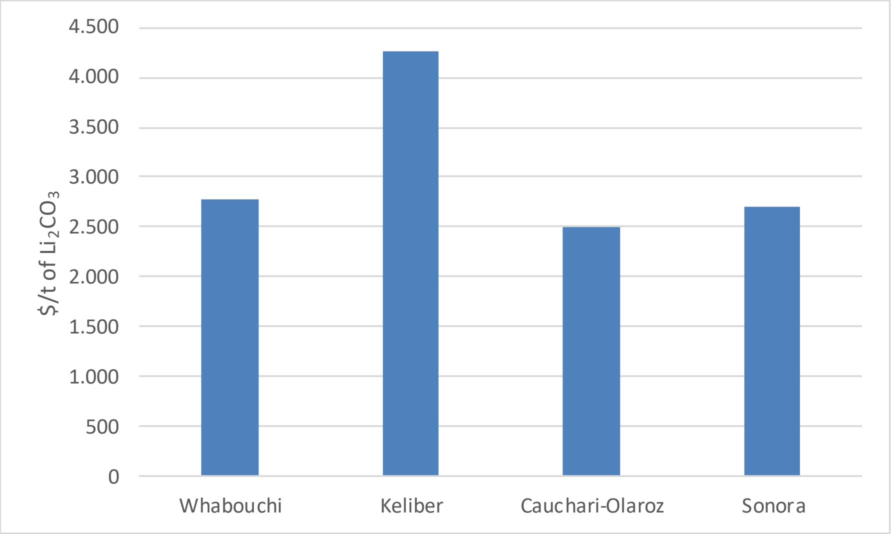

Figure 8. Operating costs in $/t of Li_2CO_3

Whabouchi, Cauchari-Olaroz, and Sonora, have almost the same operating costs in $/t of Li_2CO_3. Thus, it can be stated that salars does not represent a push out of the market for the rest of lithium-bearing deposits.

8.6. Financial outcomes

Financial outcomes of the assessed lithium projects are presented in Table 23. Net present value (NPV) has been calculated with a discount rate of 8% but Pilgangoora, which used a 10% discount rate. All presented results are after-tax.

Table 23. Financial outcomes of the analysed projects on an after-tax basis

Project	**NPV (M$)**	**IRR**	**Payback period (years)**
Whabouchi	924.7 (8%)	30.3%	2.7
Keliber	56.1 (8%)	13%	7
Cauchari-Olaroz	807 (8%)	23.5%	4
Sonora	542 (8%)	25%	5
Pilgangoora	280 (10%)	46.7%	2.1

Nevertheless, NPV should be calculated by using the real weighted average cost of capital (Krzemień, Riesgo Fernández, Suárez Sánchez, & Diego Álvarez, 2016). Vaněk, Bora, Maruszewska & Kašparková, (2017) clearly stated that in the case of hard coal, each company has a different weighted average cost of capital, although involved in the same sector. An alternative to this could be to follow the AIM Rules - Guidance for Mining and Oil & Gas Companies (London Stock Exchange plc, 2006) and discount after-tax cash-flows at a 10% rate, something much more conservative and appropriate than a small 8%.

Finally, forecasted prices that were used to develop the financial analysis are shown in Table 24.

Table 24. Forecasted prices used by the different projects

Project	Product	Forecasted price ($/t)
Whabouchi	LiOH-H_2O	9,500
	Li_2CO_3	7,000
Keliber	Li_2CO_3	4,266
Cauchari-Olaroz	Li_2CO_3	12,000
Sonora	Li_2CO_3	6,000
Pilgangoora	Spodumene	538.8

Addressing Li_2CO_3 prices and exceptuating the case of Cauchari-Olaroz, where the forecasted price is bigger than the estimated probable upper limit for the next future (10,000 $/t), the rest of the projects use very conservative figures, thus achieving lower NPVs and internal rates of return (IRRs) than should be expected.

9. CONCLUSIONS

After establishing a comparison between lithium market behaviour and the evolution of dysprosium oxide market, as well as developing lithium prices time series analysis, they are expected to return to a more stable behaviour (below 10,000 $/t) despite the increasing demand, mainly based on: (1) a ramping up of the production by miners, (2) the return to an offer and demand equilibrium with prices fixed by mining costs with normal mining market margins, and (3) the fact that there are sufficient lithium recoverable resources in order to ensure the demand of future electric vehicles. Moreover, recycling of lithium batteries will represent a significant supply for the future.

On the other hand, the economic and technical aspects of the different lithium mining investment projects were analysed, allowing to give an order of magnitude of this mining industry in order to facilitate the development of preliminary economic assessments of future mining projects: cut-off grades, dilution and extraction ratios, metallurgical recoveries, capital expenditures and operating expenses.

From this analysis, two aspects can be highlighted: (1) it was possible to establish a linear correlation between the capital expense of the lithium mining investment projects and their expected production of lithium carbonate; and (2) continental brine deposits, where the extraction of lithium is conducted by evaporation processes in man-made ponds, will not represent a push out of the market for the lithium extracted from hard rocks and clays using conventional mining methods as they have almost the same operating costs.

Finally, financial outcomes of the assessed lithium mining projects achieve lower NPVs and IRRs than should be expected as forecasted LCE prices that were used were very conservative in most of the cases. On the other hand, the use of an 8% discount rate instead of the real weighted average cost of capital compromises the reliability of the presented NPVs.

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Figure Caption:
Figure 1. Lithium Carbonate min. 99.5% Li_2CO_3 battery-grade, spot prices CIF China, Japan and Korea ($/t), from the first semester of 2002 till March, 2019. Source: different market data providers
Figure 2. Dysprosium oxide prices in Europe from 2001 until 2016. Source: Riesgo García, Krzemień, Manzanedo del Campo, Escanciano García-Miranda, & Sánchez Lasheras (2018) (adapted from MetaErden GmbH)
Figure 3. Forecasted upper limit (stripped line) for future Lithium Carbonate min. 99.5% Li_2CO_3 battery-grade, spot prices CIF China, Japan and Korea ($/t)
Figure 4. Forecasted prices for Lithium Carbonate min. 99.5% Li2CO3 battery-grade, spot prices CIF China, Japan and Korea ($/t)
Figure 5. Cut-off and mineral reserves grades
Figure 6. Li_2CO_3 production in ktpa versus capex in M$
Figure 7. Operating costs in $/t of ore
Figure 8. Operating costs in $/t of Li_2CO_3

Table Caption:
Table 1. Whabouchi project capital expenditures (Met-Chem, 2016)
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