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Original article

Project economics of lithium mines in Quebec: A critical review

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A R T I C L E I N F O

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A B S T R A C T

The province of Quebec has important lithium resources that could supply the market for lithium-ion battery production. However, even if the provincial government has promoted the development of lithium-bearing ore projects, these present important technical and technological challenges. In this line, this paper provides a critical review focusing on the project economics of mining projects under development, in order to determine the extent to which they may be an impediment to obtaining the necessary funding. Since they all involve the exploitation of pegmatites, it is interesting to compare them with the project economics reported by producers of lithium carbonate from brines in South America. Although brine mining has become popular, the increased demand for lithium combined to local factors mean that today, there is no longer a significant difference favoring them in terms of operating costs.

1. Introduction

The demand for lithium-ion batteries, mainly for the manufacture of Electric Vehicles (EV), has triggered an unprecedented interest for lithium (COCHILCO, 2017). The resulting price surge for lithium-based products has generated a renewed interest in exploration and mining of lithium deposits for the last few years. Lithium is of particular interest because it possesses many attractive properties, such as high energy density, low self-discharge, low maintenance and greatly reduced costs, which have made lithium-ion batteries superior to other commercial options on the market (IRENA, 2017). As a result, even if the estimated lithium demand for the EV batteries sold in 2019 was about 17 kt, in 2030, it should expand to around 185 kt/year considering the current policies. In a more aggressive sustainable development scenario, the consumption could reach figures more than twice as high as this forecast according to the International Energy Agency (IEA, 2020).

Lithium occurs primarily in lithium pegmatites (Australia, China, and Canada) or in the form of high-lithium brine deposits (Garret, 2004), which are mainly found in an area known as the "Lithium Triangle" in three South American countries, namely Argentina, Bolivia and Chile. In this context, Quebec, which possesses the largest lithium mineral reserves in Canada, presents the infrastructure and knowledge to integrate its potential lithium production from pegmatites into a local production chain to add additional value (Ibarra-Gutiérrez et al., 2021a). Previous work also demonstrated that the development of lithium mineral reserves in Quebec would be competitive in terms of GHG emissions due to the low emission factor for its electricity grid (Ibarra-Gutiérrez et al., 2021b). Two ventures in Quebec could start production in a foreseeable future, namely Nemaska Lithium (Whabouchi Project, planning the production of lithium hydroxide) and North American Lithium (Quebec Lithium Project, planning the production of lithium carbonate equivalent), but both present important technical and technological challenges. Other projects in various stages of development are also active in the province, but operating lithium mines and battery producing plants are yet a reality to materialize.

Since the provincial policies promote the development of lithium production projects, making a priority to foster the development of a local production chain oriented towards the market for batteries for EVs, it is important to analyze whether the associated mining costs may make the Quebec lithium projects, although more environmentally advantageous, less attractive to investors. Accordingly, this work addresses two main objectives:

1. identify, from the feasibility studies of Quebec lithium mining projects, the list of associated mining costs for these projects in terms of operating expenditures;

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2 compare these mining costs with those reported by other lithium projects elsewhere in the world in order to find trends and opportunities for improvement to make Quebec production economically attractive.

The core of the manuscript is organized as follows. Section 2 presents the methodology while Section 3 provides a comprehensive background and critical literature review about the two main methods of exploiting lithium sources, and the parameters that define the unit cost of operation. Section 4 presents the details of the results obtained, while Section 5 assesses Quebec's opportunities with respect to the economic attractiveness of potential provincial lithium projects. Finally, Section 6 highlights the major findings of the paper and provides perspectives on future work.

2. Methodology

The first part of this paper focuses on comparing the different types of commercial lithium exploitation emphasizing on the associated unit operations. The definition of unit operating cost follows to use a common language of comparison. In this regard, since there is no formal or standard definition concerning the unit cost of operation, it is a question of making a differentiation of the elements that will be grouped together.

In a second step, the values of different operations worldwide were analyzed with respect to the values reported for Quebec operations. In that sense, only those coming from technical reports (feasibility or pre-feasibility studies) in compliance with the Canadian standard NI 43-101 or any equivalent will be considered as reference. It should also be noted that, among these reports, the review considers only those from the last ten years. This delimitation primarily seeks at only referring to projects with recent information that could start in the near future.

To complete the analysis, other important economic parameters are highlighted for the projects under consideration. These include capital costs, the net present value (NPV) and internal rate of return (IRR), which provide a more complete picture of the economic factors that lead to a decision to proceed with a mining project.

Three lithium projects in Quebec with proven mineral reserves identified in a recent study (Ibarra-Gutiérrez et al., 2021b) were taken as a basis for comparison, namely Nemaska Lithium – Whabouchi, North American Lithium – Quebec Lithium, Sayona Mining – Authier Lithium. The Rose-Li-Ta project is not considered here as it does not exhibit proven mineral reserves and intends to produce Tantalum as a by-product (Critical Elements Corp 2017), which influences the unit operating costs. On the other hand, five recent brine mining projects with proven mineral reserves, located in Argentina and Chile, were identified for the purpose of comparison.

3. Background information

3.1. Lithium exploitation

Due to its reactivity, lithium metal never occurs freely in nature and is instead found in the form of lithium compounds in four main deposit types: minerals, brines, sedimentary rocks and sea water (Speirs and Contestabile, 2018). Among these, the two commercial sources of lithium are minerals and brines (Welhan, 2019).

3.1.1. Minerals exploitation

There are more than 145 different lithium-containing minerals, but only a handful, namely spodumene, lepidolite, petalite, amblygonite and eucryptite, currently present a commercial interest. Among these, spodumene (a lithium-rich granitic pegmatite) represents the most abundant lithium ore (Talens-Peiro et al., 2013) with the main producers located in Australia, Brazil, China, Portugal and Zimbabwe. Other spodumene deposits around the world (for example, in Quebec, Canada) contain large reserves of lithium that have not been mined (Bradley et al., 2017).

The processing route for spodumene ore follows conventional mining and processing, similar to many other hard rock operations. The ore is mined via drill and blast methods, then excavated and trucked to a central processing facility. After multiple stages of crushing and grinding, the spodumene can be concentrated from gangue minerals via dense media separation using either spirals and/or cyclones, both being density-based processing unit operations (Welhan, 2019). For example, the typical process for obtaining lithium carbonate equivalent (LCE) considers 12 steps after mining extraction as presented in Fig. 1. It should allow producing 99.96% LCE battery grade concentrate by Quebec Lithium. Aluminum and sulfur represent the only notable impurities, which require a bicarbonate polishing step (Canada Lithium Corp., 2012). In the case of the Whabouchi Project, there are three purification and filtration steps to remove the excess of acid and impurities such as calcium, silicon, iron, aluminum, manganese and magnesium (Nemaska Nemaska Lithium, 2019). The solution is further polished in an ion exchange system that removes trace amounts of remaining calcium and magnesium.

Although pegmatites are not particularly unusual, lithium-bearing ones are relatively rare. They have nonetheless been the predominant source of lithium for many decades, and it is only following the development of continental brine operations in recent years that the share of lithium supply sourced from pegmatites reduced (Evans, 2014).

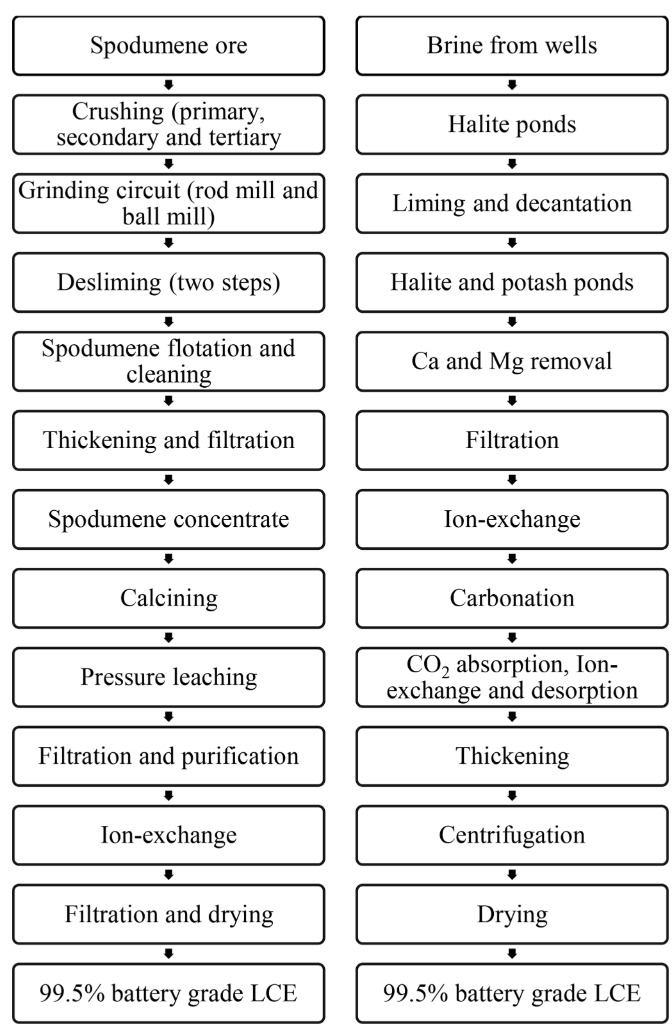

Fig. 1. Flowsheet to obtain battery grade LCE from hard-rock minerals (left) and from brines (right). Source: Elaborated from data from (Canada Lithium Corp. 2012) and (Advantage Lithium 2019).

3.1.2. Brine exploitation

The most abundant source of lithium-rich brine is the high-altitude continental brine aquifers (salars) of the Andean mountain region in South America, generated by the evaporation process due to the inverse relationship between atmospheric pressure and altitude (Kavanagh et al., 2018). Major salars exist in three countries, namely Argentina, Bolivia, and Chile, where 50% of global lithium reserves are found (Martin et al., 2017). According to Bradley et al. (2017), brine deposits share several characteristics such as:

- an arid climate;
- closed basin containing a salt lake or salt flat;
- tectonically driven subsidence;
- associated igneous or geothermal activity;
- lithium-bearing source rocks;
- one or more adequate aquifers to host the brine reservoir; and
- sufficient time to concentrate a brine.

In brine deposits, the naturally occurring solution is pumped to open man-made ponds, where solar evaporation is used to concentrate the lithium into a smaller volume of water. The brine is transferred through a series of these ponds, becoming progressively more concentrated, until the lithium can eventually be extracted by chemical means, as lithium chloride or more commonly lithium carbonate (Kavanagh et al., 2018). The typical process for obtaining LCE from brine in salars, as for the Cauchari JV Project in Argentina, considers different steps after pumping brine from wells as indicated in Fig. 1.

Brine processing presents its own set of inherent challenges. In fact, the suitability of brine deposits for production of lithium depends on the composition of the brine, including its lithium concentration, as well as the volume, accessibility, and its amenability to local processing (Kesler et al., 2012). In that line, potential complications include the possibility that removal of large volumes of brine will result in dilution of remaining brine and that reaction between recharge waters and salt-bearing host rocks will cause degradation of reservoir and brine properties (Kesler et al., 2012). On the contrary, higher grades of lithium and higher evaporation rates decrease the amount of time the brines must be in evaporation ponds (Mohr et al., 2012).

3.2. Unit operating cost

Costs of a potential project can be estimated through a variety of techniques. The estimation of cost is an extremely important part of the project economics. In a feasibility study, all possible costs are generally estimated to ensure a proper economic evaluation (San Miguel, 1996). According to the Mining Engineering Handbook (SME, 2011), definitions of unit operating cost and the various elements they include may vary from one company or author to another. However, they can be understood in a general way as being the cost associated with the extraction of an economic quantity of material, and its subsequent minerallurgical processing up to the exit of the processing plant, including all the operations involved in achieving this objective. Gentry and O'Neill (1984) indicate that operating costs are defined as three primary categories, namely direct, indirect and general expenses, which are classified as follows:

- direct operating costs
  - labor: direct operating, operating supervision, direct maintenance, maintenance supervision, and payroll burden on the foregoing labor,
  - materials: maintenance, repair materials, processing materials, raw materials, consumable energy,
  - royalties,
  - development (production area);
- indirect operating costs
  - labor: administrative, safety, technical, service (clerical, accounting, general office), shop and repair facilities, and payroll burden on the foregoing,
  - insurance (property, liability),
  - depreciation,
  - interest,
  - taxes,
  - reclamation,
  - travel, meetings, donations,
  - office supplies, upkeep, utilities,
  - development (general mine);
- general expenses.

From a more mining-operational point of view, the unit operating cost is generally composed of the addition of three main categories of costs: mining costs, processing costs and indirect costs, which include environmental, administrative and other costs (Planeta and Paraszczak, 2001). Based on the aspects previously indicated, the unit operating cost should generally include the elements described hereafter.

- Mining costs
  - Cost of preparatory work: this cost includes the completion of all work required to prepare and access the working front — both at the extraction level (lower) and the drilling level (upper), in the case of underground mining. In particular, it includes the crosscuts in the waste and in the ore as well as all operations related to their development. Other costs that may be perceived as necessary for the preparation-operation-planning of a stope/working front, such as definition drilling, may be included in the cost of preparatory work.
  - Cost of services and support: where geotechnical conditions and/or the design of the stopes or the mining front require it, the bench, the foot wall, the hanging wall or the roof must be supported in order to ensure their stability and safe working conditions for employees. The most commonly used support techniques are bolting and cable bolts.
  - Costs of drilling and blasting: this cost includes expenses related to drilling and blasting operations. According to Lopez-Jimeno et al. (1995), drilling costs includes, among other things, insurance, interest and depreciation associated with the drill rig as well as costs related to energy, lubricants, wear and tear on drilling tools and their replacement, and associated labour. Furthermore, the same authors report the costs associated with blasting depend primarily on the type of explosive chosen, but must also consider accessories, such as detonators, primers, detonating cord, etc.
  - Mucking and transportation costs: this cost considers the expenses of extracting the estimated mineral reserve after blasting and handling it to the specified locations. Depending on the logistics planned for each operation, this handling may be done in successive stages, using different equipment working in series when greater distances are to be covered.
  - Other mining costs: this category allows the grouping of all items associated with the mining cost that have not been specifically included in another category. As previously mentioned, there is no precise definition of unit operating cost in terms of the elements or categories that must comply with it; mining companies are therefore free to work with their own criteria.
- Processing costs: this cost corresponds to the expenses related to the minerallurgical processes that must be applied to the material extracted from the mine, the run-of-mine, in order to concentrate and/or obtain the metal of interest. Such processes may include, but are not limited to, secondary crushing of ore, grinding (with autogenous, semi-autogenous, ball or other mills), separation (flotation, magnetic, leaching or other), and concentration/purification.
- Indirect costs: this category includes all other costs associated with operations necessary for the economic production of the metal of

interest that have not been included in the cost of mining or processing. Included in this category are the cost of ventilation/air conditioning, hoisting, engineering and/or technical, administrative and environmental services. Again, the categorization is quite flexible and may vary from one mining company to another.

Due to their specific characteristics, lithium brine operations do not have the same categories that define the unit operating cost for underground or open pit operations. In this sense, although the literature does not offer a standard categorization for the unit cost of operation when the ore is extracted from brines, the analysis of feasibility studies of operations of this type has identified certain elements in common, thus resulting in the following grouping with respect to this study:

- salt removal and transport;
- chemical reagents;
- energy (thermal and/or electrical);
- manpower, catering and camp services;
- product handling system operation and maintenance;
- indirect costs (general expenses and administration).

4. Results

Table 1 reports the main characteristics of Quebec's lithium mining projects considered in this study. The expected final product differs from one project to another. While Authier Lithium is expected to produce spodumene concentrate, the Quebec Lithium and Whabouchi are expected to generate a more elaborate product, namely LCE for the former, and lithium hydroxide monohydrate (LMH) for the latter. It is only since very recently that producers started focusing on LCE for battery applications. This notwithstanding, lithium hydroxide also represents a key battery cathode raw material. More a niche product than LCE, it is also used by major battery producers that are competing with the industrial lubricant industry for a limited supply (DrM 2019).

Based on the respective feasibility studies, Table 2 lists the operating costs for the three above-mentioned projects. It should be noted that various items were grouped according to the categorization proposed by Planeta and Paraszczak (2001), defined in Section 3.2. It must be emphasized that since the three mines have a different final product, costs have been expressed in terms of the tonnage milled, and in terms of the final product.

The literature review identified five lithium projects that will use brines as raw material. Table 3 summarizes the main characteristics of them, and Table 4 details their unit operating costs.

The unit operating costs listed in the project economics of lithium mining projects for obtaining LCE from brines in the countries of the Lithium Triangle (Table 4) appear to be in the range between 3,000–3,600 USD/t LCE, except for the MSB Blanco project in Chile. In fact, this project has substantially higher costs, mainly for energy and manpower. In Chile energy is more expensive than in Argentina due to its strong dependence on fossil fuels, especially in the north of the country. Moreover, manpower cost is higher in Chile since there is a strong mining tradition with high competition for skilled labor. In fact, Table 4 illustrates that chemical reagents along with energy and manpower are the most important cost items.

On the other hand, the capital expenditures (CAPEX) associated with each project and listed in Table 5 should obviously not be overlooked (Fig. 2). Hence, it may be more attractive for investors to choose a

Table 1
Characteristics from the different Quebec's lithium mining projects.

Parameter	**Authier Lithium**	**Quebec Lithium**	**Whabouchi**
Proven reserves	6.1 Mt	6.6 Mt	19.0 Mt
Life of mine	14 years (open pit)	15 years (open pit)	26 years (open pit) 7 years (underground)
Concentrate of spodumene production	114,116 t/y	165,000 t/y	215,000 t/y
Concentrate grade	6.00% Li_2O	5.7-6.5% Li_2O	6.25% Li_2O
Further processing	No	Yes	Yes
Final production	—	20,000 t of LCE/y	37,000 t/y of $LiOH.H_2O$

Sources: Sayona Quebec, 2019, (Canada Lithium Corp. 2012) *and* Nemaska Lithium, 2019.

Table 2
Unit operating costs from Quebec's lithium mining projects.

Cost category	Authier Lithium	Quebec Lithium		Whabouchi	
	USD/t milled	USD/t milled	USD/t LCE	USD/t milled	USD/t LMH
Mining costs	19.46	18.84	1,153.07	20.34	597.55
Processing costs	16.82	37.70	2,308.40	16.07	472.11
Indirect costs	12.61	2.21	135.13	27.52	808.49
Total (USD/t milled)	48.89	58.75	—	63.93	—
Electrochemical plant	—	—	—	—	1,762.73
Total (Final product)	—	—	3,596.60	—	3,640.87

Notes:
i) For the purpose of comparison, all values have been discounted to December 2020 U.S. dollars using the rates listed on the United States Department of Labor (U.S. Bureau of Labor Statistics, 2021) from the dates indicated in the respective feasibility studies.
ii) For each project, the conversion rates reported in their feasibility study were used.
iii) Certain values in $/t milled or $/t LCE were estimated from the average parameters for each project when not directly available on the feasibility studies.
*iv) Sources:*Sayona Quebec, 2019, (Canada Lithium Corp. 2012) *and* Nemaska Lithium, 2019.

Table 3
Characteristics from different brine lithium mining projects.

Project name	Country	Life of mine	Targeted production	Source
3Q Project	Argentina	35 years	20,000 t of LCE/y	(NEO Lithium Corp. 2019)
Cauchari JV	Argentina	31 years	25,000 t of LCE/y	(Advantage Lithium 2019)
Cauchari-Olaroz	Argentina	40 years	40,000 t of LCE/y	(Lithium Americas 2019)
Pastos Grandes	Argentina	40 years	24,000 t of LCE/y	(Millennial Lithium 2019)
MSB Blanco	Chile	20 years	20,000 t of LCE/y	Minera Salar Blanco, 2019

Table 4
Unit operating costs from brine lithium mining projects.

Cost element	3Q Project	Cauchari JV	Cauchari-Olaroz	Pastos Grandes	MSB Blanco
Salt removal and transport	370.23	530.37	468.88	520.80	502.92
Chemical reagents	1,494.14	1,727.75	1,838.05	2,043.62	1,076.20
Energy	323.44	268.22	388.88	182.74	1,063.78
Manpower, catering and camp services	427.19	282.39	349.38	264.97	582.60
Carbonate transport and maintenance	171.89	544.54	434.45	365.48	550.52
Indirect costs	176.98	67.81	142.79	60.91	127.28
Total (USD/t LCE)	2,963.87	3,421.08	3,622.43	3,438.52	3,903.30

Note: For the purpose of comparison, all values have been discounted to December 2020 U.S. dollars using the rates listed on the United States Department of Labor (U.S. Bureau of Labor Statistics, 2021) from the dates indicated in the respective feasibility studies.

Table 5
Detailed capital expenditures from the analyzed lithium projects.

Project	CAPEX (USD)				
	Direct costs	Indirect costs	Sustaining capital	Other	Total
Authier Lithium	92,207,306	29,757,352	91,802,444	—	213,767,103
Quebec Lithium	188,851,729	43,902,352	31,304,129	—	264,058,210
Whabouchi	612,379,084	237,847,504	231,588,359	142,239,067	1,224,054,015
3Q Project	251,958,592	24,508,935	210,541,985	58,086,834	545,096,346
Cauchari JV	322,119,291	54,179,637	72,875,149	108,660,895	717,755,436
Cauchari-Olaroz	464,321,984	67,850,759	273,934,780	206,387,831	1,012,495,354
Pastos Grandes	356,907,988	47,594,161	103,551,641	132,085,194	640,138,984
MSB Blanco	471,931,138	46,391,550	54,844,910	85,486,658	658,654,256

Notes:
i) For the purpose of comparison, all values have been discounted to December 2020 U.S. dollars using the rates listed on the United States Department of Labor (U.S. Bureau of Labor Statistics, 2021) from the dates indicated in the respective feasibility studies.
ii) The designation "Other" includes differed CAPEX, contingencies and working capital as well as all values presented in the feasibility studies that are not included in another category.
iii) In the case of Whabouchi project, CAPEX includes both Whabouchi/Chibougamau/Matagami site CAPEX and Shawinigan site CAPEX.

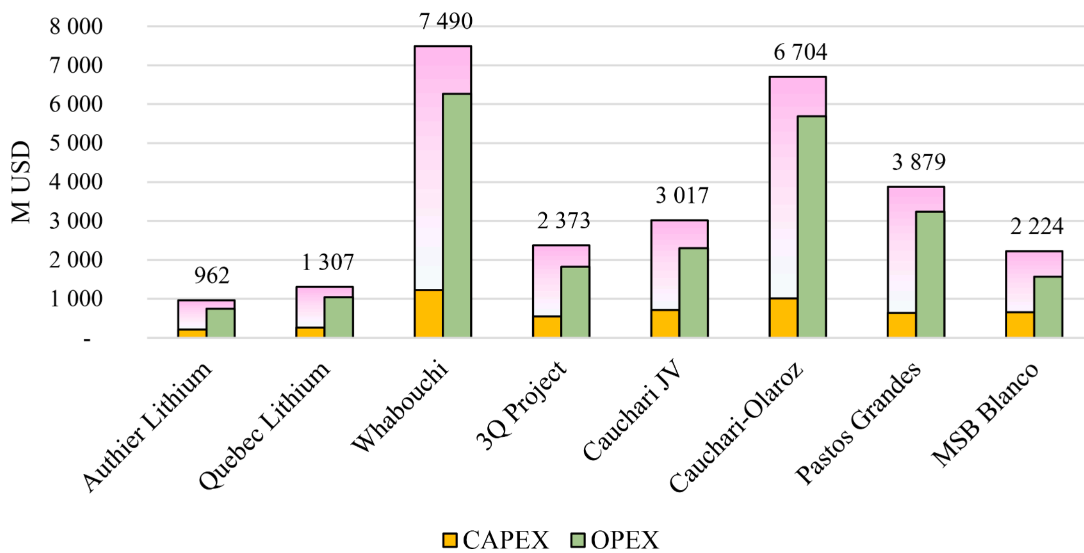

Fig. 2. CAPEX and OPEX over the life of mine from the analyzed projects.

project with a higher operating cost providing it would offer a higher internal rate of return (IRR), higher net present value (NPV) and/or lower risk (Table 6).

Table 6
Project economics from analyzed lithium mining projects.

Project name	NPV	IRR	Payback Period	Source
3Q Project	1,547 M USD	60.30%	1.7 years	(NEO Lithium Corp. 2019)
Cauchari JV	1,158 M USD	26.20%	4.6 years	(Advantage Lithium 2019)
Cauchari-Olaroz	2,774 M USD	37.99%	2.8 years	(Lithium Americas 2019)
Pastos Grandes	1,588 M USD	28.10%	5.3 years	(Millennial Lithium 2019)
MSB Blanco	1,286 M USD	23.80%	4.1 years	Minera Salar Blanco, 2019
Authier Lithium	216 M CAD	33.90%	4.0 years	Sayona Quebec, 2019
Quebec Lithium	365 M CAD	32.00%	4.0 years	(Canada Lithium Corp. 2012)
Whabouchi	3,128 M CAD	30.30%	4.5 years	Nemaska Lithium, 2019

Notes:
i) Presented values correspond to pre-tax net present values (NPV) at 8% discount rate.
ii) Presented values correspond to pre-tax internal rates of return (IRR).
iii) Presented values correspond to pre-tax payback periods.
iv) Presented values have not been discounted and are reported according to the date of the feasibility studies.

5. Discussion

The results indicate that the Quebec Lithium Project (planning the production of LCE), for unit operating costs of about 3,600 USD/t LCE, can be compared with the upper range of salar projects in Argentina. They are equivalent to that of Cauchari-Olaroz (3,620 USD/t LCE), but slightly lower than that of the MSB Blanco (3,900 USD/t LCE). Only 3Q Project, at ~3,000 USD/t LCE, exhibits notably lower unit operating costs. For the remainder, Cauchari JV and Pastos Grandes, the difference is ~200 USD/t LCE in favor for them.

Pavlovic (1990) provided a very different picture of the production landscape some thirty years ago, reporting Fig.s for spodumene processing doubling that for brines: 1,100 USD/t of LCE at Atacama, Chile, versus 2,430 USD/t of LCE at Bessemer City, North Carolina. Even in 2016, the Deutsche Bank (2016) was estimating a significant offset, ranging from 2,500 to 4,000 USD/t of LCE, for brines, and between 4, 500 – 8,000 USD/t of LCE for spodumene. It is only very recently that conventional spodumene lithium projects started being seen as economic viable alternatives (Sterba et al., 2019).

Several factors contribute at closing the gap for the potential lithium projects in Quebec as presented hereafter.

- Low electricity costs in the province: in June 2020, the average cost of industrial electricity in Chile was 0.151 USD/kWh and that of Argentina 0.044 USD/kWh (GlobalPetrolPrices, 2021), while the price of electricity in Quebec's industrial sector remains one of the

lowest in North America, and this advantage tends to increase over time (MERN, 2021). As an example, the Whabouchi project, in its feasibility study, reports an electrical power cost of 0.0378 USD/kWh (0.0492 CAD/kWh) for year 1 to 4 and 0.040 USD/kWh (0.052 CAD/kWh) for the remaining years (Nemaska Lithium, 2019).
- Close proximity to established infrastructure (power lines, highways, water supplies, etc.) for projects close to urban areas located in the Abitibi-Témiscamingue region.
- No requirement for on-site infrastructure such as accommodation camps and power plants for projects close to urban areas located in the Abitibi-Témiscamingue region.
- Presence of an historical mining expertise and a qualified local workforce.
- Favorable geology.
- Proximity to the potential market for electric vehicles in the United States.

In the same perspective, it can be noted that the development of spodumene lithium deposits will have a notable advantage: the speed at which lithium carbonate can be produced (Scales, 2011). Only five days are needed between the time the ore is mined and the final product is ready for shipment. In countries such as Australia and Chile, brine evaporation can take between 18 and 24 months. This time can be considerably longer if there is an unexpectedly high rainfall event onto the ponds (Welhan, 2019).

Moreover, recent research work shows that advanced process control is a very interesting avenue to increase the economic performance and reduce the energy consumption of mineral processing operations. Bouchard et al. (2017) analyzed and highlighted the effect of the process control system design on the energy footprint of a grinding circuit, emphasizing that properly designing a control system appears to be a very practical and low-cost option. In the same line, Pérez-García et al. (2020) evaluated the benefits of explicitly integrating online mineral liberation data in control systems for grinding-separation circuits, and the results obtained are already encouraging. This kind of development could potentially be used to offset the cost of producing lithium carbonate from Quebec's mines as flotation constitutes the de facto mineral processing route to produce lithium carbonate from most pegmatites. The grinding, heating, and dissolution steps in this process are expensive and are the reasons that many pegmatites are at a disadvantage compared to brines, which can be treated to release lithium much more easily (Gruber et al., 2011). Stamp et al. (2012) report that the Cumulative Energy Demand (CED) to produce one kilogram of LCE from brines was 28.43 vs. 33.87 MJ eq for spodumene.

Except for the Whabouchi project, where the construction of the electrochemical plant in Shawinigan represents an important part of the capital cost, the other two Quebec ventures have a lower CAPEX than the Salar projects. These results coincide with those of Johnston (2019), who indicates that lithium carbonate plants producing from brine deposits have a significantly higher capital cost than spodumene plants.

The same author indicates that reagent costs, while significant for both types of operation, make up a smaller fraction of the overall operating cost for plants producing spodumene ore. The global expenditures over the life of the mines obtaining LCE from brines tend to exceed that from spodumene, a trend that was also reported by Johnston (2019).

The Nemaska Lithium venture stands alone in this analysis by targeting a different final product, namely lithium hydroxide monohydrate, to reach a niche market. Other lithium projects elsewhere in the world follows a similar path, for instance Zinnwald Lithium in Germany, which focus on lithium fluoride production (LiF). The manufacturing process of $LiPF_6$, the most common conducting salt for lithium-ion batteries uses lithium fluoride. In this particular case, the final product was changed from LCE/LMH to LiF, to increase project economics (Deutsche-Lithium, 2019).

In this regard, it may be that a final product with a higher selling price may offset a higher unit operating cost (or capital costs) or, conversely, other companies may aim for a final product with a lower value but which would avoid large investments to start an operation. In any case, several factors come into play, including comparative advantages and demand projections for the expected final product as well as the expected production. As an example, although the operating cost for Whabouchi and Quebec Lithium are comparable, the final products are different and Whabouchi's operating cost of the electrochemical plant represents 48.41% of the total.

In addition, the NPV of lithium mining projects from pegmatites in Quebec is much lower than that of lithium mining projects from brines as shown in Table 6. The Whabouchi project does not follow this trend because it is a large deposit with mineral reserves that allow for an operating period of over 30 years, more than doubling that of other projects in the province. In fact, except for the MSB Blanco project, all other projects in the salars have operating periods of more than 30 years. Finally, with respect to the Quebec projects, they all have an IRR between 30-34%, while a greater variance is observed for this parameter in the brine projects, ranging from 24-61%.

Lastly, the Quebec government promotes the development of a local battery production chain based on lithium mining in the province not only for economic outcomes, but also for sustainability motivations. Atlin and Gibson (2017) explain this concept of using mines and mining as a bridge to a sustainable future. The bridging requires a joint venture between the industry and the government to develop opportunities where a portion of the revenues supports specific programs on a regional as well as a project-by-project basis. The development of lithium projects could offer Quebec a unique opportunity thus to contribute to the development of the communities involved according to their needs. Bergeron (2021) shows that defining the socio-geological potential of a territory provides a holistic outlook of the possibilities for mining development that combines geology with other fundamental characteristics of a territory, namely those that its human occupation entails. This proposal aligns with recent research demonstrating that the mineral development in Canada now requires both impact and benefit agreements with communities and permits with regulators (Collins and Kumral, 2021).

6. Conclusions

The Province of Quebec bears the largest lithium mineral reserves in Canada and three projects exhibit proven mineral reserves. Based on their project economics, as reported on the respective feasibility studies reports, the unit operating costs to produce one ton of LCE from pegmatites would be comparable to those of other projects where LCE is obtained from brines.

While the literature reports this general trend for spodumene lithium producers, several additional regional factors for the province support the competitiveness of these projects. Recent process control developments could also help to further reduce their unit operating costs, particularly with respect to one of the most expensive stages, namely ore processing.

The projects analyzed however show that lithium mining projects from brines are of a larger scale in terms of life of mine, capital costs involved and NPV. Four out of five lithium in brine projects display a life of mine exceeding 30 years, compared to 15 years or less for two out of three of spodumene projects.

On the other hand, further work should be done in order to explore the significance of the location and other market aspects as factors that can significantly influence the decision to proceed or not to proceed with a lithium mining project. This would allow, in the particular case of Quebec projects, the comparison with other producers of lithium from pegmatites, such as given projects in Australia and China. The absence of an international bank of technical studies (feasibility, pre-feasibility) as well as the difficulty to adapt the formal guidelines for calculating reserve and resource estimates to the reality of brines, such as NI 43-101 or JORC Code, limit the scope of the study.

Despite these limitations, this study provides a context for compiling, interpreting and comparing results from different projects and highlights the fact that the operating cost of obtaining lithium carbonate from brines is no longer necessarily lower than from mineral exploitations.

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Declaration of Competing Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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