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Abstract

In the path towards decarbonization, rechargeable lithium-ion batteries are critical for the widespread adoption of electric vehicles and renewable energy storage systems. To meet the growing demand for this mineral, various sources of lithium are being explored. This study evaluated the technical and economic feasibility of direct lithium extraction (DLE) from flowback and produced waters (FPW) of the Duvernay shale reservoir development near Fox Creek, Alberta and the Montney tight reservoir development in Northeast British Columbia using ion-exchange sorbents. Results indicate that lithium extraction from FPW using DLE technology is a viable option, with fluid pH, temperature, total suspended solids, and organic carbon affecting extraction efficiencies. In the assessment of Duvernay-based FPW fluids processed at a selected centralized facility, approximately 93 tonnes of lithium carbonate, or 105 tonnes of lithium hydroxide monohydrate could be produced annually, based on an average lithium content of 45.1 mg/L and a capacity of approximately 475,000 m^3 per year. A discounted cash flow analysis determined the after-tax and royalty internal rate of return of 22% in the production of lithium carbonate (Li_2CO_3), and 38% in the production of lithium hydroxide monohydrate ($LiOH \cdot H_2O$) from the Duvernay development area. Comparatively, in the assessment of Montney brine fluids processed at a modelled centralized facility, approximately 117 tonnes of lithium carbonate or 134 tonnes of lithium hydroxide monohydrate could be produced annually, based on an average lithium content of 57.7 mg/L and a capacity of approximately 475,000 m^3 per year. A discounted cash flow analysis determined the after-tax and royalty internal rate of return

of 29% in the production of lithium carbonate and 48% in the production of lithium hydroxide monohydrate from the Dawson Creek Montney development area.

These findings demonstrate the economic feasibility of extracting and refining lithium into battery-grade products from a novel source based on forecasted commodity prices and the development of a domestic battery supply chain system. Further investigation of DLE technology, a strategic resource sampling and analysis program, and investigation into the minimum scale of lithium extraction development are recommended.

Chapter 1. Introduction

As nations contend with the transition to low-carbon economies and achieving net-zero targets, specific sectors assume a critical role in the pathways to decarbonization. Canada's transportation and electricity generation sectors, as the second and sixth largest sources of greenhouse gas emissions, respectively (Environment and Climate Change Canada, 2021), play a vital role in these strategies. Rechargeable battery systems and their respective use within Electric Vehicles (EVs) and energy storage devices supporting renewable power generation are playing an increasingly important function in the pathway to decarbonization.

The adoption of electric vehicles is anticipated to serve as a key contributor towards reducing emissions in the transportation industry. The International Energy Agency forecasts that light-duty EVs will account for nearly 75% of all new vehicle sales by 2030 (International Energy Agency, 2021), with sustained adoption over the long term as internal combustion engines reach the end of their respective lives. Domestically, the Government of Canada has indicated that, by 2035, all new light-duty cars and passenger trucks sales will be zero-emission (Transport Canada, 2021). The adoption of Battery Electric Vehicles (BEVs) presents a significant opportunity for lowering emissions, as they do not generate any greenhouse gas emissions during usage (Doluweera et al., 2020). It is important to note that the effectiveness of BEVs in reducing emissions is linked to the emissions intensity of the source of electricity production. Thus, any emissions reduction relies heavily on improvements to electricity generation. In connection with this, incorporating of energy storage systems, such as

Battery Energy Storage Systems (BESSs), can enhance the utilization of renewable energy generation by addressing the intermittency of the energy sources.

Lithium battery formulations, including lithium phosphate, lithium polymer, and most prominently, lithium-ion, are expected to maintain a significant position in the energy storage and EV sector due to their superior energy density (W-h/kg) and specific density (W-h/L), as compared to traditional rechargeable batteries. Increasing adoption of Lithium-Ion Batteries (LIBs) for EVs and BESSs has significantly increased the demand for raw battery minerals.

The United States Geological Survey (U.S. Geological Survey) estimates that raw lithium material demand for use in the manufacturing of lithium batteries has grown by over 500% between 2015 and 2020 (Jaskula, 2016, 2021). Beyond this historical growth profile, significant future pressure on the lithium supply system is expected due to increased market demand for LIBs that align with increasing EV market penetration (Roskill Information Services Ltd., 2021a). From this, one must consider the raw material sources necessary to fulfill this increasing demand and whether the existing supply chain has the capacity to do so.

Given the increasing importance of lithium, there are opportunities for Western Canada to be a key producer to support LIB manufacturing. Further, the existing oil and gas industry in Western Canada could leverage its existing infrastructure and contribute to the transition of energy to support the net-zero goal by 2050.

With the ever-increasing importance of critical minerals, investigations into the extent and overall potential of lithium production from oilfield brine within Western Canada have garnered attention from all levels of government, the oil and gas industry, and the investment community. Efforts have been made to assess the extent of the resource and to promote initiatives that seek to advance the technologies required for extracting lithium from source brines in Western Canada. This study intends to assess the opportunity to produce lithium from select oilfield brines in Western Canada

1.1. Background

Flowback and produced Water (FPW) from the oil and gas industry is a type of oilfield brine generated during hydraulic fracturing and production operations of unconventional hydrocarbon reservoirs. Historically, FPW has been treated as wastewater, and it continues to be an area of concern for the industry, the regulators, and the public in Canada. As the oil and gas industry strives towards minimizing their respective environmental impacts, including freshwater usage, the challenge remains on managing the current FPW production while implementing economically feasible treatment or disposal strategies. This research aims to assess the technical, financial, and environmental feasibility of extracting dissolved lithium minerals from produced wastewater at existing hydrocarbon processing facilities within Alberta and British Columbia (B.C.).

1.2. Scope and Objectives

This study assesses the technical challenges, environmental implications, and financial opportunities for lithium developments associated with a waste stream produced within select oil and gas developments. This work investigates the viability of lithium production from two brine sources: 1) FPW from the Devonian Duvernay Formation shale reservoirs near Fox Creek, Alberta, and 2) FPW from the Triassic Montney Formation tight reservoirs near Dawson Creek, British Columbia. This study is limited to the recovery of lithium from source waters and the manufacturing of lithium battery chemicals, which can subsequently be utilized to produce end-use products further along the value chain.

To accomplish this research goal, the following objectives were defined:

1. Assess the chemical composition of FPW associated with the Duvernay Shale formation in Alberta and the Montney formation in northeastern British Columbia.
2. Identify and investigate any patterns or variations of the lithium concentrations in the collected data.
3. Evaluate the technical applicability of various lithium extraction processes and technologies based on the associated FPW fluid chemical composition. From this, develop capital and operating cost models for the extraction of lithium from FPW.
4. Identify operational considerations in the production of lithium from FPW brines in centralized oil and natural gas production facilities.

5. Create a financial model to produce lithium battery chemicals which integrates the chemical and physical parameters found in FPW, together with variations in capital and operating costs, over a range of commodity prices.

1.3. Summary of Research Methodology

First, it is relevant to comprehend the present market and supply situation of raw lithium materials, which involves assessing the worldwide and local production and distribution of lithium as a resource. Existing and forecasted supply and demand trends are considered, including the identification of end-use markets and consumer demands. Various raw lithium sources, including mineral ore and brine fluids, are explored, with a review of the existing production processes. From this, advancements in DLE processes are evaluated for their applicability in developing lithium production from oilfield brines in Western Canada.

This study develops a cost model for lithium extraction and production by evaluating representative large-scale, brine-based lithium operations that are either already established or proposed. Analytical chemistry results for about 400 FPW samples from the Duvernay and Montney formations were acquired through a variety of sources (Kingston et al., 2023) and were utilized in the creation of the lithium production scenarios. Customized cost models and lithium production scenarios are developed to create a Discounted Cash Flow (DCF) model to determine the financial viability of potential lithium developments from oilfield brines. The DCF model was used to estimate the total supply costs, associated taxes and royalties, the profitability of investments, internal rates of return, and technical input parameters that determine the investment profitability. The viability of extracting lithium from FPW brines co-produced alongside current oil and gas projects is evaluated based on the results of the DCF model.

This study concludes by addressing the research questions, summarizing the project limitations, and providing recommendations on future research opportunities.

Chapter 2. Background Information

As the third element in the periodic table, lithium is an alkali metal that exhibits high reactivity in the presence of oxygen, and due to this, it is not found in its elemental form in nature (Speirs et al., 2014). Lithium is also the most polarizing of the alkali metals, having a high electrochemical potential to accumulate chemical energy efficiently (Kavanagh et al., 2018). Globally, lithium is not considered a rare mineral as it is the 33rd most abundant element in nature, and noted to have a relatively broad distribution throughout the continental crust (Aral & Vecchio-Sadus, 2019). However, it does not generally occur in concentrations considered economically feasible to extract, except in select regions of the world. The approximate range of background lithium abundances in the general environment is presented in Table 1.

Table 1: Typical lithium background concentrations and abundances in the environment (from Aral & Vecchio-Sadus, 2019).

Environmental Media	Concentration or Abundance
Freshwater (mg/L)	0.00007 – 0.04
Seawater(mg/L)	0.17-0.19
Sediment (mg/kg, or ppm)	56
Soil (mg/kg, or ppm)	3-350
Earth’s Crust (mg/kg, or ppm)	20-60

2.1. Critical Minerals in Canada

The efforts towards decarbonization have resulted in various supply chain uncertainties, leading individual countries to formulate critical mineral lists. These resources are viewed as vital to this transformation, are geographically concentrated, and are prone to (or have) the potential for supply disruptions (Kalantzakos 2020). Canada, in turn, has created the Canadian Minerals and Metals Plan (CMMP) which identifies 31 defining minerals, including lithium, as a recognition of the importance of these resources (NRCan 2020a). The federal government believes that these critical minerals will be the building blocks for a clean and digitized economy, are essential to Canada's economic security, and can be a sustainable and secure source of critical minerals for our partners (NRCan 2021a).

In 2020, Canada entered into a strategic partnership with the United States after signing the Canada-U.S. Joint Action Plan on Critical Minerals Collaboration (NRCan 2020c). The joint action plan between Canada and the United States has identified the lithium supply gap. The action plan aims to develop a lithium supply chain from mineral extraction to manufacturing and eventually to recycle lithium-ion batteries (Granholm 2021). To ensure a dependable and diversified supply of lithium, technology companies, exploration companies, battery suppliers, and vehicle manufacturers are consistently forming strategic alliances and joint ventures (Jaskula 2021).

These partnerships intend to strengthen the domestic supply chain security and reduce the reliance on foreign producers and imports while offering increased transparency on critical raw mineral supply chains. The mounting pressure to decarbonize and the associated need for large-scale electrification has driven the demand for lithium and, from this, has presented an opportunity to deploy DLE technology to produce lithium from Western Canadian brine fluids.

2.2. Lithium Demand and Market Uses

There are different types of lithium battery chemicals, including lithium carbonate (Li_2CO_3) and lithium hydroxide monohydrate ($LiOH \cdot H_2O$). Thus, reporting lithium quantities and mass of the various products can be confusing. The markets for lithium materials are most commonly expressed as units of lithium carbonate equivalent (LCE). For example, from a unit of mass perspective, 1 unit of contained lithium (Li^+) mineral is equivalent to 5.323 units of lithium carbonate (LC), or 6.046 units of lithium hydroxide monohydrate (LHM). Other relevant lithium compounds and their respective conversion factors, including lithium oxide (Li_2O), which is the form of lithium used to describe the ore grade from hard rock mineral sources, are provided in Table 2. When discussing the various lithium compounds, one must be mindful of the chemical under discussion, as both the elemental lithium content and the product's value can significantly vary.

Table 2: Conversion factors for lithium and selected compounds (from British Geological Survey, 2016)

		To convert to:		
To convert from:	**Chemical Formula**	**Lithium content**	**Lithium oxide content**	**Lithium carbonate equivalent**
Lithium	Li	1	2.153	5.323
Lithium oxide	Li_2O	0.464	1	2.473
Lithium carbonate	Li_2CO_3	0.188	0.404	1
Lithium chloride	LiCl	0.163	0.362	0.871
Lithium bromide	LiBr	0.08	0.172	0.425
Lithium hydroxide mono-hydrate	$LiOH \cdot H_2O$	0.165	0.356	0.88

Traditional uses of lithium include their application in the manufacturing of glass and ceramics, lubricating greases, polymer production, metallurgical applications, welding fluxes, pharmaceuticals, and air treatments (Kavanagh et al., 2018). Lithium demand from traditional applications is estimated at 22,500 tonnes (~120,000 tonnes LCE) in

2021. Beyond this base demand, a forecasted 600% increase in demand for LIBs through 2030 is expected to put significant pressure on the lithium supply (Roskill Information Services Ltd., 2021a). Although there are ranges of future demand estimates, there are indications that by 2030, approximately ~1.6 to 3.3 million tonnes of LCE will be required to satisfy the various LIB demand market segments, as presented in Figure 1 and the EV-specific demands, as illustrated in Figure 2.

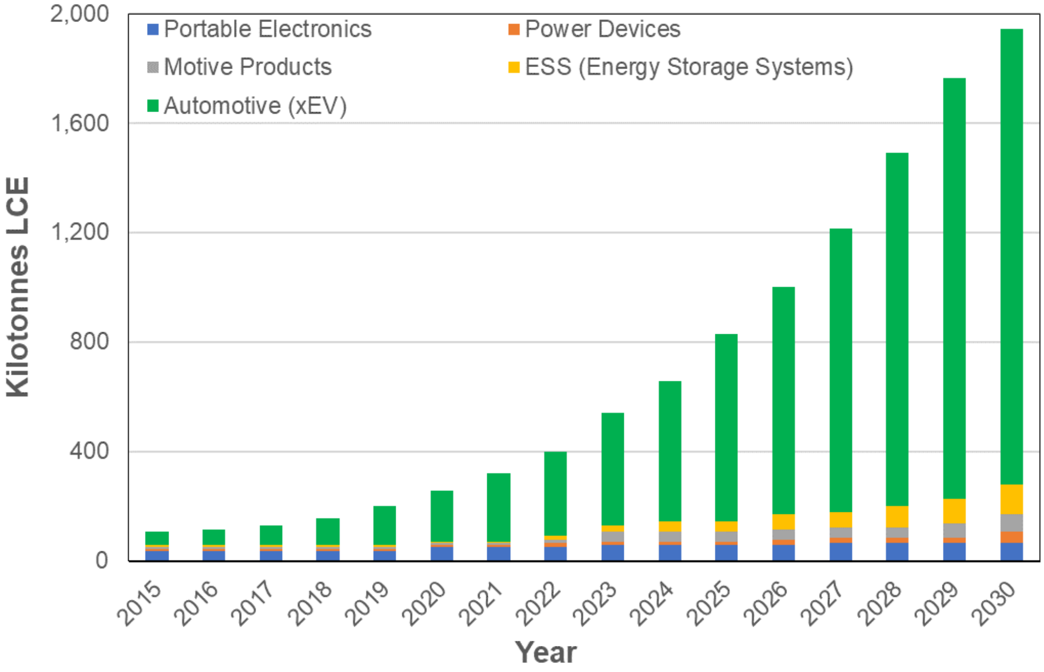

Figure 1. Forecasted lithium demand by application (based on data from Roskill Information Services Ltd., 2021a).

A representation of the various pathways from raw lithium sources (including brines and mineral ores), through intermediate lithium products, to the associated end-use products is represented in Figure 3. For this study, it is worth noting the pathways from raw materials to the intermediate battery chemicals (lithium hydroxide and lithium carbonate), to the lithium-ion battery end-use product, and their subsequent application in EVs, consumer electronics, industrial & energy storage devices.

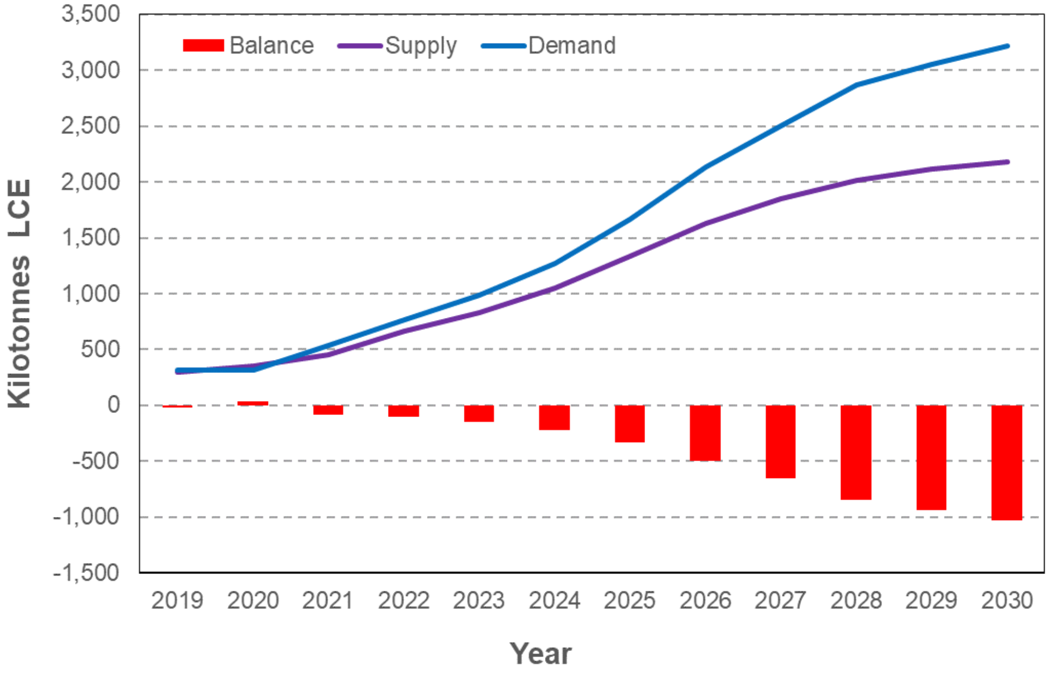

Figure 2. EV battery supply/demand forecast deficits (based on data from Fastmarkets, 2022).

From a production perspective, the National Minerals Information Center of the U.S. Geological Survey reported that the annual global production of lithium materials increased gradually from 2000 through 2015, with a dramatic increase in annual production occurring in 2016. According to the U.S. Geological Survey (2015), lithium compounds used in the global end-use battery market remained below 30% of global production until 2015. From 2016 onwards, the share of lithium production allocated to the global end-use battery market steadily increased. More recently, the U.S. Geological Survey (2021) estimated that in 2020, 71% of total global lithium production was allocated to the end-use battery market. The estimated annual global lithium production and the corresponding share of global lithium production allocated toward battery manufacturing are presented in Figure 4.

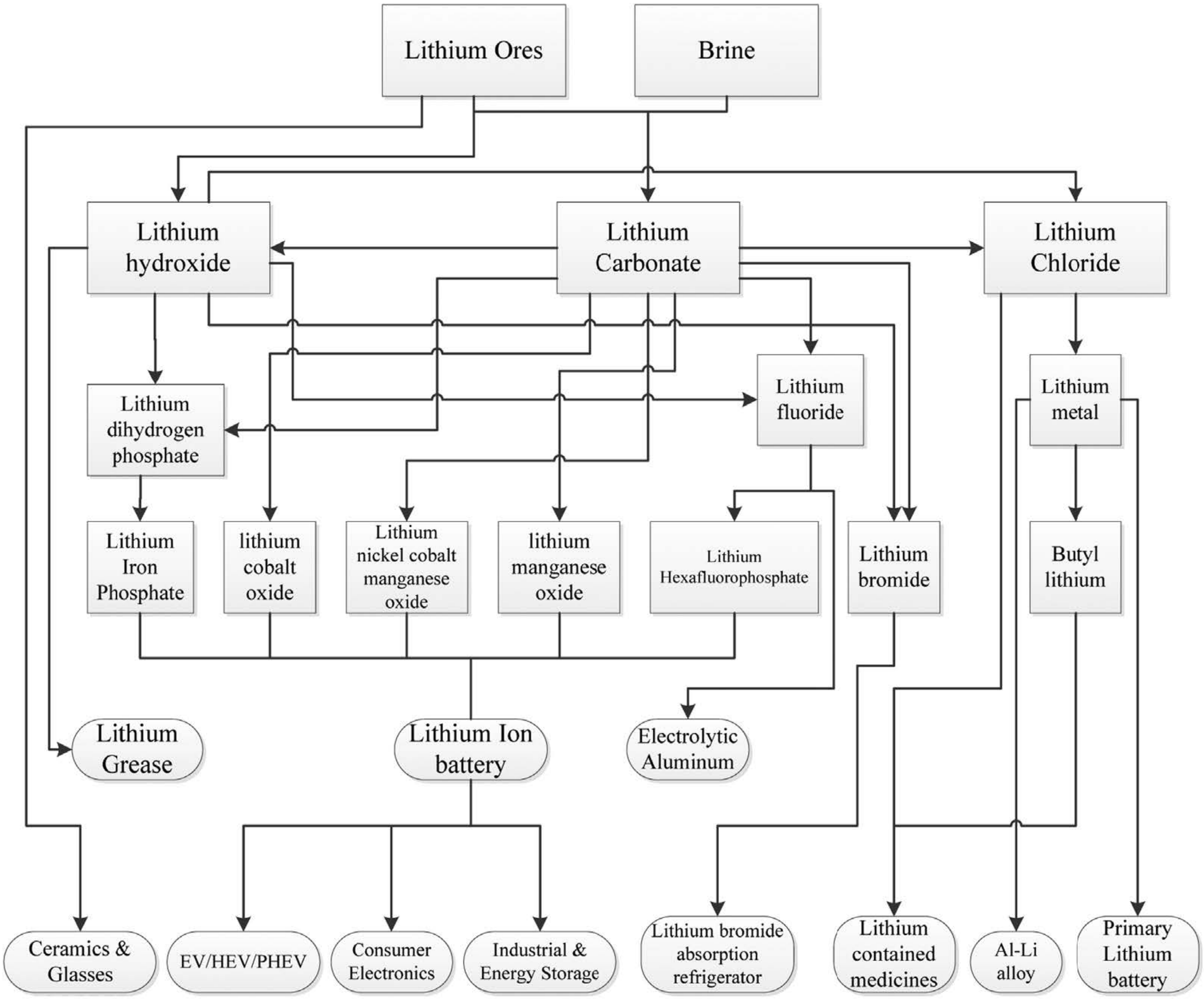

Figure 3. Production and use of major lithium compounds by source (Lu et al., 2017, reproduced with permission from Elsevier).

In 2020, the global production (excluding U.S. production) of lithium (Li^+) material was approximately 436,000 tonnes LCE, with U.S. production “withheld to avoid disclosing company proprietary data” (U.S. Geological Survey, 2021, p. 98). Given that lithium production in the U.S. is estimated to range from 1% (Blackmon, 2021) to 5% (Zeng et al., 2019) of the total global production, there is a minimal effect on the quantities presented.

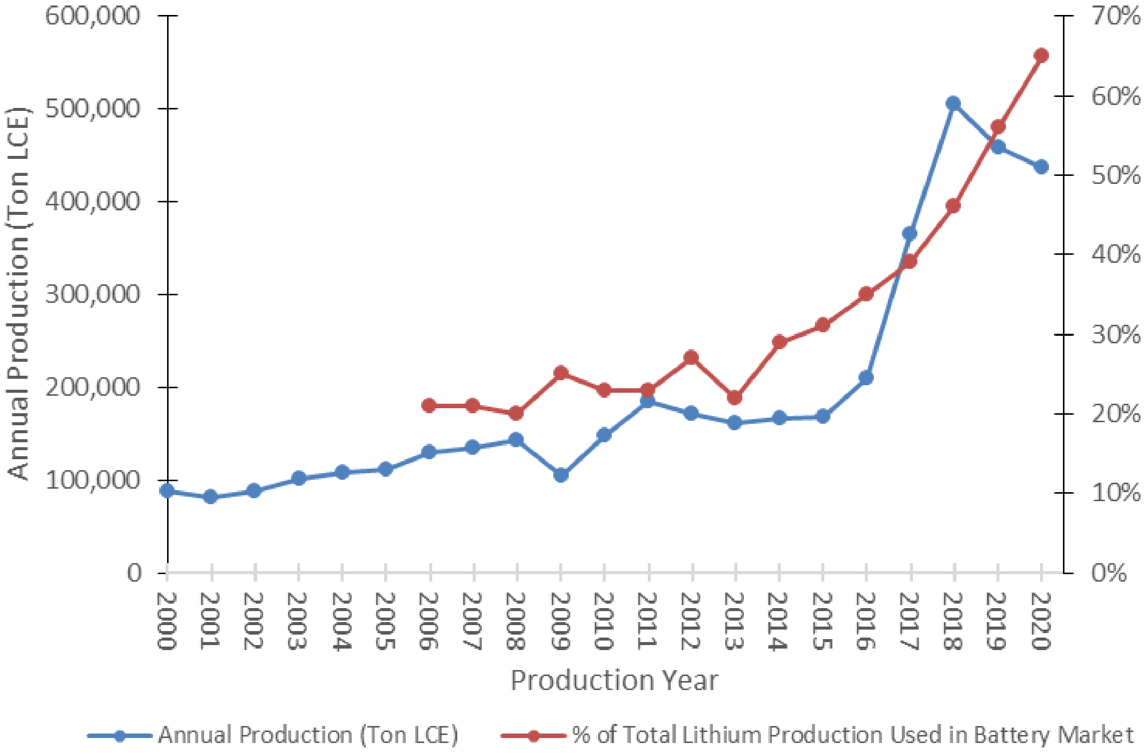

Figure 4. Estimates of global annual lithium production and production share to battery market (U.S. Geological Survey, 2021).

Based on the estimated market share of lithium materials used for battery manufacturing (71% in 2020), approximately 310,000 tonnes LCE were utilized in the production of LIBs in 2020. Lithium market forecasts by Roskill Information Services Ltd. (2021) indicate that as early as 2030, the rechargeable battery end-use market consumption will increase to approximately 90% of all lithium resources produced.

2.3. Lithium Resources, Reserves and Production

Global resources (as tonnes of lithium content), which include the sum of source materials considered economic for production, marginally economic for production, and sub-economic for production, have increased from approximately 39 million tonnes in 2015 (U.S. Geological Survey, 2015), up to approximately 86 million tonnes in 2020 (U.S. Geological Survey, 2021). Reported lithium resource quantities have been increasing owing to new discoveries and expanded exploration programs, likely a result of the forecasted supply and demand profiles. Resources contained within the lithium triangle area, a region between Argentina, Bolivia and Northern Chile, total approximately 49.9 million tonnes, or 58% of the global resources. Canada and the United States each contain resources of approximately 2.9 million tonnes and 7.9 million tonnes, respectively (Jaskula, 2021).

A detailed breakdown of the global lithium resources by country is presented in Figure 5. It should be noted that although the estimates of the total resource quantities and the quantities from the various regions will differ based on the reporting agency, Flexer et al. (2018) indicate that there is general agreement that the lithium resources in brine deposits are significantly larger than those in hard rock sources. Swain (2017) also indicate that approximately 65% of all known lithium resources are from brine deposits, with the remainder from hard rock mineral deposits.

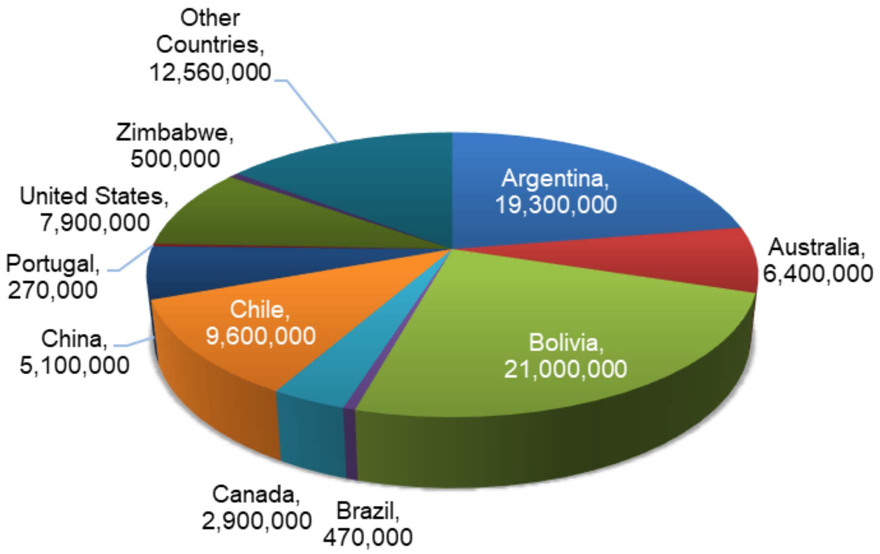

Figure 5. Global lithium resources by country as tonnes of lithium content (U.S. Geological Survey, 2021).

Similarly, global reserves (as tonnes of elemental lithium), which are considered resources that can be economically extracted or produced, have increased from 13.5 million tonnes in 2015 (U.S. Geological Survey, 2015) to 21.0 million tonnes in 2020 (U.S. Geological Survey, 2021). The two countries containing the largest economically recoverable reserves are Chile, with 9.2 million tonnes in brine-based deposits, and Australia, with 4.7 million tonnes in mineral-based deposits. Canada and the United States each retain approximately 530,000 tonnes and 750,000 tonnes of lithium reserves, respectively (U.S. Geological Survey, 2021). A breakdown of the global lithium reserves by country is presented in Figure 6.

Current estimates of global production by the U.S. Geological Survey (2021) indicate that Australia accounts for approximately 49% of global production, while Chile, China, and Argentina's production account for 22%, 17% and 8%, respectively (Figure 7). From a source perspective, global refined lithium production is estimated to be 57% from hard rock mineral sources, 38% from brine sources and 5% from recycling operations (Mitchell, 2021).

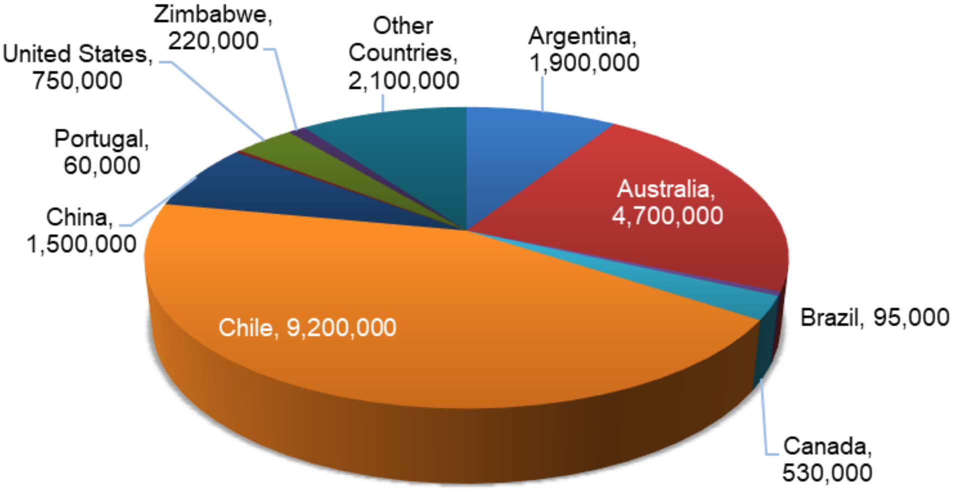

Figure 6. Global lithium reserves by country as tonnes of lithium (U.S. Geological Survey, 2021).

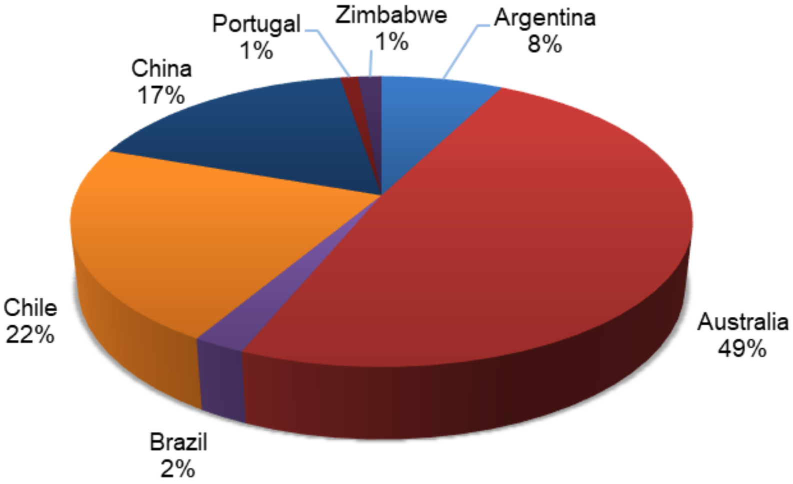

Figure 7. Global lithium production by country (US Geological Survey, 2021).

2.4. Lithium Sources

2.4.1. Lithium from Mineral Sources

The most abundantly produced source of lithium is from hard rock ores, specifically pegmatite, a type of igneous rock composed of a variety of minerals including quartz, feldspar, mica, albite, and lithium-bearing minerals (Tadesse et al., 2019). The lithium-bearing minerals contained within the pegmatites include spodumene ($LiAl(SiO_3)_2$), petalite ($LiAlSi_4O_{10}$), and lepidolite ($K(Li,Al)_3(Al,Si,Rb)_4O_{10}(F,OH)_2$). Due to the extensive occurrence of individual deposits, spodumene is the most common commercially mined lithium-bearing mineral (Champion, 2019). With ore grades of up to 3.9 wt.% lithium oxide, a majority of Australia's lithium resources, and thus significant global production, is sourced from this high-quality mineral deposit (Champion, 2019). However, spodumene is also the most difficult to process among all of the lithium-bearing minerals. In its natural state, spodumene is resistant to commonly used ore leaching techniques, thus requiring additional thermal preprocessing known as decrepitation or roasting (Karrech et al., 2020). A summary of the various lithium-containing mineral ores, general information regarding the deposit types, and the respective lithium grade and concentrations found in nature are presented in Table 3.

Similar to other mineral-producing ore operations, the extraction of lithium from its parent material is intensive, complicated, and customized using a combination of pyrometallurgical (thermal) processes and hydrometallurgical (aqueous chemical) processes. A generalized process flow of the extraction of lithium from mineral sources is presented in Figure 8 for reference.

Table 3: Key features of common lithium-bearing deposits for current lithium production in the world (Adapted from British Geological Survey (2016)).

	Deposit Type	**Notes**	**Typical Grade or Concentration**
Hard Rocks	LCT Pegmatite	Coarse-grained igneous rock containing spodumene, lepidolite, and petalite formed during the late-stage crystallization of magmas.	1.5-3.9 wt.% Li
	Lithium Clay	Lenses of smectite clay (hectorite) in association with volcanic centers	0.54 wt.% Li
	Jadar-type	Altered sediments in an enclosed basin	1.5 wt.% Li
Brines	Continental	Salt pans or salars in enclosed basins with lithium enrichment from hot springs	400-1500 mg/L Li
	Geothermal	Elevated levels of lithium contained in steam at geothermal power stations	100-350 mg/L Li
	Oilfield	Elevated levels of lithium contained in waters or brine produced in oilfields	100-500 mg/L Li

The process of obtaining lithium minerals from their source material involves crushing and grinding the source ores, also referred to as comminution, to physically separate the different minerals from the original material matrix. The lithium-containing pulverized minerals are then concentrated from the waste minerals, or tailings, by exploiting the physical, electrical, and magnetic properties of the various minerals contained within the ores (known as beneficiation) (Kavanagh et al., 2018). The remaining processing to extract lithium is customized based on the nature of the material and the specific intermediate lithium chemical selected. Various combinations of thermal, chemical and electrochemical processes are used to remove impurities, concentrate the lithium mineral, and leach the lithium into a solution (Tran & Luong, 2015). Lithium concentrate solutions are purified using chemical precipitation methods, concentrated through ion exchange or re-dissolution and evaporative techniques, and then converted to a usable product such as LC or LHM through electrodialysis, crystallization, or carbonation processes (Tran & Luong, 2015).

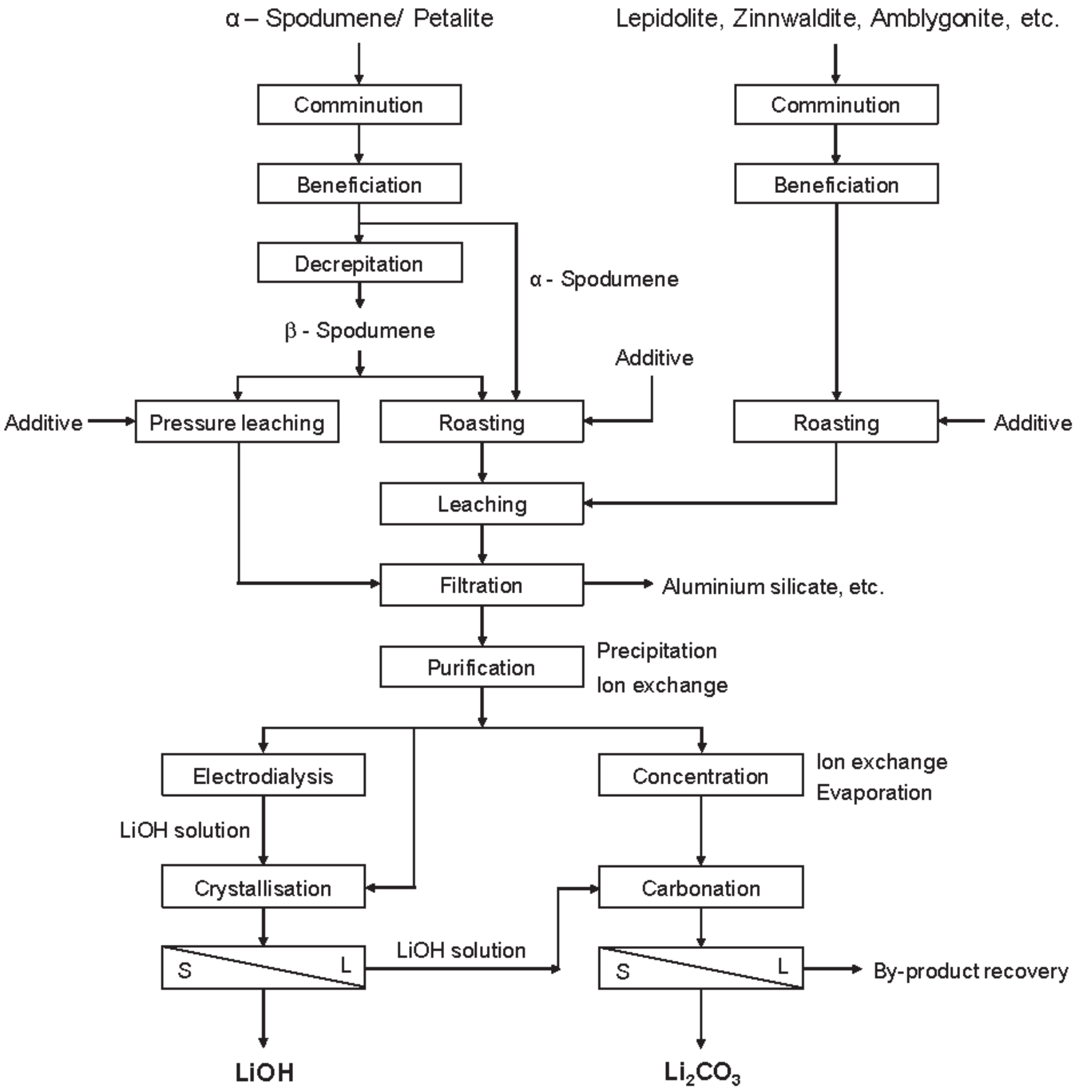

Figure 8. Generalized process flow for production of lithium from mineral sources (Tran & Luong, 2015, reproduced with permission from Elsevier). The specific “additives” utilized during processing will differ based on the ore mineralogy and the process selected by the company or service provider. “L” and “S” indicate Liquid and Solid physical state separation.

2.4.1.1. Environmental Impacts of Lithium Extraction from Mineral Sources

Understanding the possible environmental effects and issues related to lithium extraction from mineral sources is essential. Among these issues, the most notable include the magnitude of the surface area disruptions that the process entails, the management of the waste materials and leachate, and the high energy requirements associated with extracting lithium from hard rock mineral ores.

Large-scale surface disturbances from greenfield development operations result in significant de-vegetation or deforestation, and these could result in soil erosion, sedimentation, and surface water quality impacts. For example, according to Dupéré et al. (2018), the development and operation of the Whabouchi lithium mine located in the Province of Quebec could result in an open-pit mine with a maximum depth of 223 m and an affected pit area of approximately 36 hectares. Apart from the area where the ore is directly mined, the processing facilities and other associated infrastructure required for the mining operation would also affect a larger surrounding area. Given the extent of the surface disturbances, interim and final reclamation of the surface impacts require significant planning, and are an ongoing concern given the long lifespan of the developments.

For reference, at the Whabouchi lithium mine, the average grade of the spodumene ore for proven and probable mineral reserves is 1.53% Li_2O (Dupéré et al., 2018). During the lifespan of the development and operations, the open-pit mine is expected to generate 32.7 million m^3 of waste rock and 12.9 million m^3 of associated tailings to produce a total of approximately 792,000 tonnes of LCE (equivalent to 33,000 tonnes LCE per year) over its 26 year expected mine life (Dupéré et al., 2018).

Tailings waste and leachate management are of particular concern in open-pit mining operations given that the natural rock is both physically and chemically altered to extract the mineral of value. Site-specific risk assessments are necessary to address the potential for high-risk waste leakage and subsequent waste management (Dupéré et al., 2018). The assessment considers the tailing's potential for metal leaching into water, radioactivity and acid rock drainage, the results of which will dictate the extent to which tailing must be contained or treated according to applicable regulations.

The environmental impacts associated with open-pit mining developments can be significant, but the probability and effects can be reduced when proper regulation and mitigation efforts are enforced. With preventative measures in place these hazards are considered manageable; however, in poorly managed mining operations, the environmental impacts can take years before becoming apparent and can continue for many decades after operations have ceased (Kavanagh et al., 2018).

When considering the impacts of lithium from mineral ore operations, the energy intensity and the energy source of the operations must be considered. According to Roskill Information Services Ltd. (2020), the average energy intensity of lithium production from mineral sources is 39,100 kilowatt-hour per tonne (kWh/T) LCE. This includes electrical and other direct fuel consumptions from all activities associated with the extraction, processing, transport and refining of the lithium from the parent material. The high and sustained temperatures required within the refining processes from mineral concentrate to end-use products, including the calcination, roasting and crystallization processes, account for a majority of the energy consumption requirements (Roskill Information Services Ltd., 2020). Overwhelmingly, the refining of ore into a lithium end product accounts for approximately 67% (26,197 kWh/T LCE) of the total energy consumption on average, while the physical mining of the parent ore is significantly less intensive at 14% of the total energy required on average (5,474 kWh/T LCE) (Roskill Information Services Ltd., 2020). Depending on the primary energy source of the mineral producer's supply chain, such as coal, natural gas, diesel, or renewable sources, the emissions intensity from the energy consumption could be of significant environmental concern.

2.4.2. Lithium from Brine Sources

Although a majority (57% in 2020) of global lithium production is from hard rock mineral sources, the remaining global production output is from lithium brine sources. Most notable of the latter are four continental brine operations located within the lithium triangle in South America, and two continental brine operations located in the Qinghai-Tibet Plateau of China (U.S. Geological Survey, 2021). These continental brine sources, with naturally occurring average lithium concentrations of up to 1,500 mg/L, are located within regions of low precipitation rates, high solar irradiation, and contained catchment areas. The brine fluids are accessible from the surface via partially evaporated lakes or shallow subsurface aquifers within large saline basins (known as salars) (US Geological Survey, 2017). A representation of a typical lithium-enriched enclosed continental basin is presented in Figure 9.

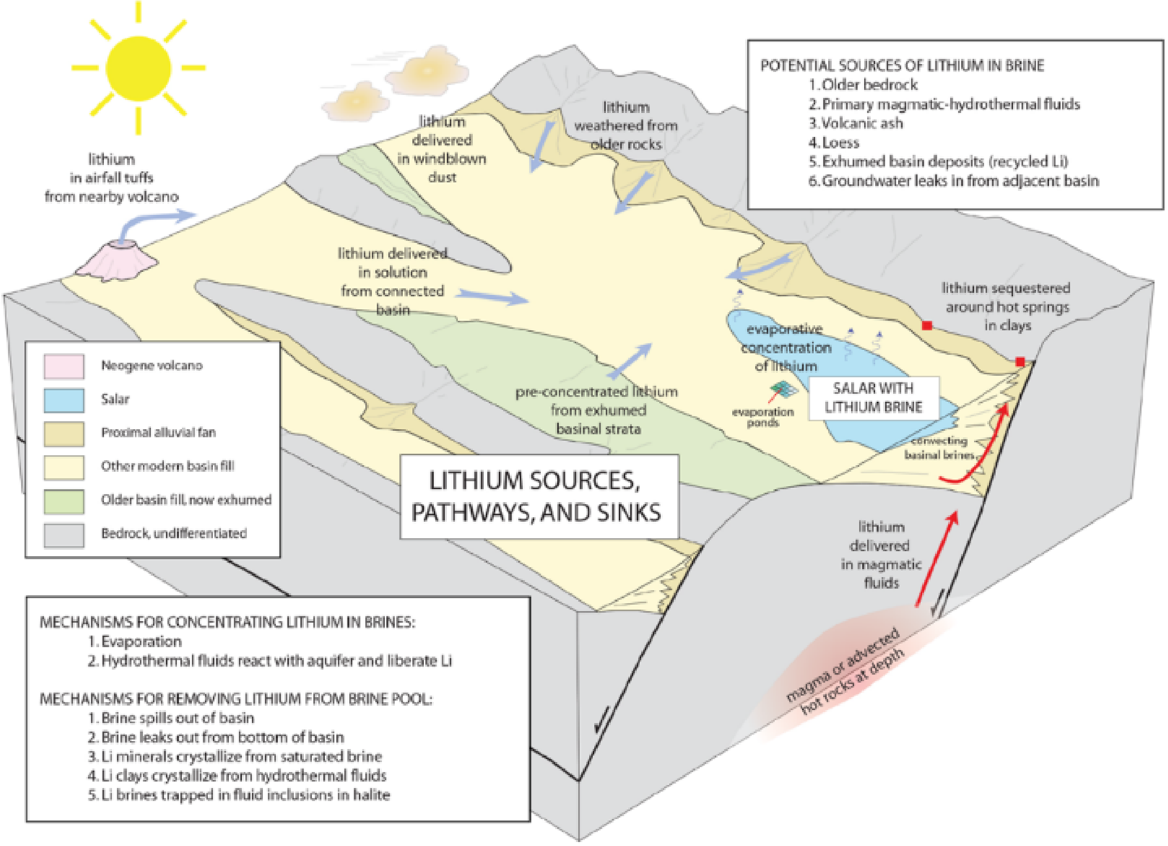

Figure 9. Schematic for the formation of a lithium brine deposit within an enclosed basin (U.S. Geological Survey, 2017).

As naturally occurring lithium is concentrated via the cycles of transport and evaporation within the enclosed basins from the parent sources, the lithium compounds generally remain in solution due to their high solubility in water. Even at high concentrations, lithium is not readily precipitated like other minerals which tend to form an evaporite mineral as the water evaporates off and the minerals reach their saturation point (U.S. Geological Survey, 2017). As the brine density increases through the evaporative cycles, the lithium-bearing solution will descend into the subsurface until restricted by a confining layer (U.S. Geological Survey, 2017).

Other common lithium-bearing brine sources include geothermal waters and oilfield brines produced along with petroleum hydrocarbons; the latter is discussed in greater detail below. A summary of the various lithium-bearing brines, general information regarding the sources, and their respective lithium concentrations are shown in Table *3*, alongside similar information for the mineral-based materials.

Comparatively, operations associated with lithium production from brine sources are simpler than that of hard rock mineral operations. Although the process of recovering lithium from brines is specific to each brine deposit, the associated mineral composition and the intended lithium end product, each development follows the generalized process flow depicted in Figure 10.

The most common production process for recovering lithium from brines is through multi-stage solar evaporation and precipitation of accompanying minerals within manufactured ponds. The lithium source brines are pumped (from surface or aquifer), at approximate concentrations ranging from 400 to 1500 mg/L, into constructed evaporative retention ponds. The subsequent multi-stage evaporative processes further concentrate the lithium in solution up to approximately 60,000 mg/L (Flexer et al., 2018).

These progressive stages of evaporation and concentration are accompanied by the precipitation of associated impurities including Na^+, Cl^-, Mg^{2+} and K^+ as they reach their respective saturation points (Tran & Luong, 2015). After achieving the predetermined lithium concentration, the brine is transferred to a recovery facility for additional purification and concentration processes.

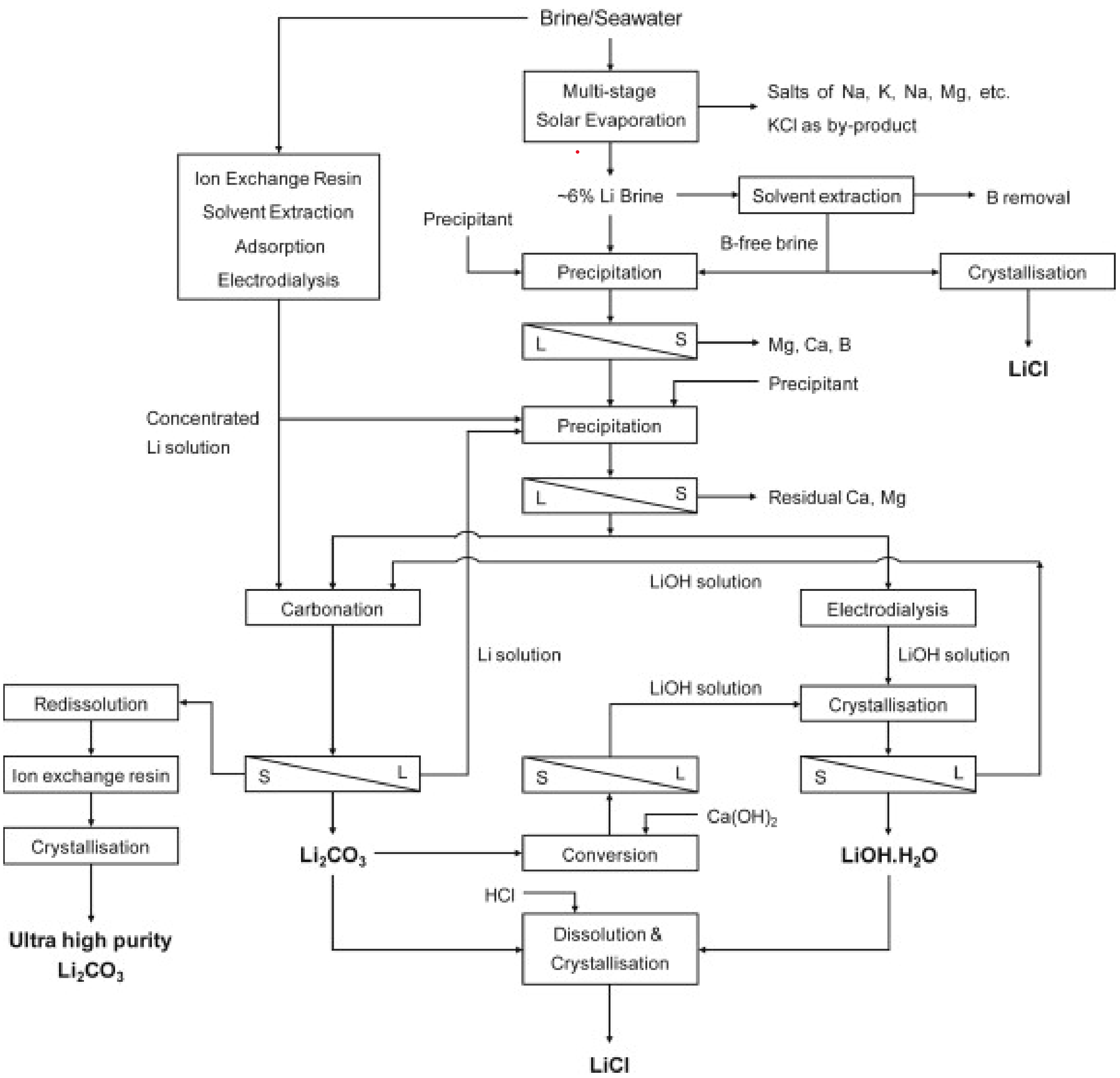

Figure 10. Generalized process flow for production of lithium from brine (Tran & Luong, 2015, reproduced with permission from Elsevier). Direct lithium extraction processes are represented to the left side of the process flow diagram, identified as ion-exchange resin, solvent extraction, adsorption, and electrodialysis.

To be suitable for use in manufacturing downstream products, including LIBs, the intermediate lithium products require extremely low concentrations of impurities (Grágeda et al., 2018; Tran & Luong, 2015). Mineral impurities not precipitated and removed within the concentrating evaporative ponds must be removed through additional treatment processes to purify the lithium-enriched solution further. The most notable contaminants within continental brines can include (but are not limited to) boron and magnesium.

Boron-based impurities are typically removed by utilizing a solvent-based extraction process to produce a boron-bearing waste solution and a boron-free lithium concentrate (Tran & Luong, 2015). Selective Mg^{2+} precipitation is often accomplished through chemical treatment and pH modification utilizing lime (CaO) to deplete the magnesium cations and increase the recovery rate of lithium from the brine source (Flexer et al., 2018). Notably, Mg^{2+} cations share similar chemical properties and ionic sizes to Li^{+} cations, which introduces difficulty in separating the two within the brine solution and impedes lithium recovery (Tabelin et al., 2021).

For lithium-bearing brines containing low concentrations of Mg^{2+} and Mg/Li ratios of <6, the conventional solar evaporative precipitative method with pH modification described above is considered a suitable process methodology (Liu et al., 2020). However, as the Mg/Li ratio increases above 6, lithium recovery rates suffer, purification and processing costs increase, and as a result, alternative processing or extraction techniques have been considered (An et al., 2012; Liu et al., 2020). Flexer et al. (2018) indicate that lithium recovery rates from continental brines and evaporative processes are approximately 50% of the original concentration on average. This is a direct result of the co-precipitation of Li^{+} with other evaporative salts, and the carryover of lithium into the various solid and liquid waste streams produced during impurity removal.

After subsequent concentration and purification, the lithium enriched brines are converted to common lithium products including lithium chloride (LiCl), lithium carbonate (Li_2CO_3) and lithium hydroxide monohydrate ($LiOH \cdot H_2O$) through electrodialysis, crystallization, or carbonation processes. Depending on the grade of lithium material required in the end-use product, additional purification processing may be required. This includes re-dissolution and precipitation, liquid-liquid (solvent) extraction, electro-dialysis, and ion-exchange membranes to increase the purity to the desired grades (Linneen et al., 2019; Tabelin et al., 2021).

Generally, lithium extraction and production operations from continental brine deposits have lower exploration costs, lower capital costs, and lower operating and maintenance costs compared to mineral ore operations (Tabelin et al., 2021). Nevertheless, the traditional evaporation and precipitation brine operations do have their suite of challenges to manage, including:

(1) Surface land impacts in the remote solar-evaporative environments of continental brine operations due to the large-scale use of manufactured evaporative ponds to concentrate the lithium;

(2) Resultant volumes of spent brine fluids to be managed from a waste perspective;

(3) The presence of other mineral impurities in the solution including boron, sodium, calcium, magnesium and potassium, leads to complexities in the processing, and management of the solid waste precipitates;

(4) Management of the phase chemistry (liquid versus solid) of the lithium mid-point and endpoint products throughout the process, which relates to net recovery efficiencies; and

(5) Long processing periods (12-24 months) from initial brine production are necessary to produce a viable lithium concentrate product due to the reliance on environmental conditions (Flexer et al., 2018; Swain, 2017).

As a result of the difficulties presented by these extraction processes and their low rates of recovery, efforts are underway to develop alternative methods for extracting lithium. To extract lithium in a more selective manner, various DLE processes are being explored, including the use of ion-exchange resins, chemical solvents, selective adsorptive materials, and electrodialysis. These methods are targeted towards brines produced within geothermal and oil and gas field developments in temperate climates (Swain, 2017; Tabelin et al., 2021).

2.4.2.1. Environmental Impacts of Lithium from Continental Brine Sources

There are two primary environmental concerns associated with the solar evaporative and precipitation processes of lithium-enriched continental brines: freshwater usage and solid waste management of the precipitated materials.

Regarding freshwater usage, lithium-from-brine using solar evaporative methods utilize groundwater drawn from discrete aquifers as part of the lithium purification process. Flexer et al. (2018) indicate that within the lithium-producing region of Argentina, between 5 and 50 m^3 of freshwater is consumed in the purification and refining process per tonne of battery-grade Li_2CO_3 produced. This freshwater is most commonly used to improve the transportability of brines, and as make-up water required by certain refining and polishing processes (Flexer et al.,2018).

Although this quantity of freshwater consumption may be considered low in many other regions of the world, these operations occur in regions where the natural precipitation is extremely low, commonly less than 20 mm per year on average, and freshwater supplies are considered scarce (Kavanagh et al., 2018). Additionally, the sheer scale of individual operations would notably affect freshwater availability within the region. For example, the Salar de Atacama of Chile produced nearly 109,000 tonnes of LCE in 2021 (Roskill Information Services Ltd., 2021b).This natural scarcity has resulted in conflicts between the agricultural community, the indigenous peoples, and the lithium production operations (Jerez et al., 2021; Kavanagh et al., 2018). Ecological and socio-economic impacts have been identified within one of the most significant lithium brine-producing regions, the Salar de Atacama, where sensitive ecosystems are present within one of the driest places on the planet, and are located within the ancestral territories of the indigenous peoples (Jerez et al., 2021). The increasing demand for lithium as a strategic mineral required in the development of low-carbon economy within the “Global North, has resulted in socio-environmental damages and water injustices in the Global South” (Jerez et al., 2021, p. 2).

Although some studies have focused on the interaction between the brine water and freshwater hydrologic systems within these enclosed basins, it is generally accepted that any significant water extraction or diversion from either system will shift the balance of the two interconnected water systems (Flexer et al., 2018). The effect of development on the hydrologic cycles in the region is unknown; however, a change in the natural balance between the freshwater and brine water interface could lead to impacts on the local flora and fauna in the the lithium triangle, an area that is described as a biodiversity hot spot (Flexer et al., 2018).

Border & Sawyer (2014) detail the need to better understand the effects of fresh and brine water removal from the environment on the hydrologic cycles to protect both the ecosystem and the lithium resource itself. Freshwater migration into the brine aquifers would reduce the availability of an already scarce freshwater resource, and concurrently dilute the lithium resource within the deposit, thus increasing processing costs to extract a unit of lithium. Increasing developments and production within the lithium-rich arid regions should be expected to increase the pressure on the scarce fresh-water resources and, as a result, the impacts on local agriculture, indigenous groups and the natural environment.

From an energy intensity perspective, lithium production from brine operations is generally less energy-intensive compared to that of lithium from mineral sources. According to Roskill Information Services Ltd. (2020), lithium production's average global energy intensity from continental brine sources is 15,800 kWh/T LCE, thus approximately 60% less intensive than that for hard rock mineral operations. The pumping and processing of the source brine into a lithium concentrate accounts for approximately 60% (9,480 kWh/T LCE) of the total energy consumption on average. While refining the concentrate into a lithium chemical is less significant, accounting for approximately 11% of total energy (1,738 kWh/T LCE). Depending on the type of primary energy source of the operations, the emissions associated with the production of a unit of lithium product from brine operations could be considered less of an overall concern compared with hard rock mineral operations due to the reduced overall energy intensity.

2.4.3. Lithium from Oilfield Brines

Increased attention has been given to alternative brine-based lithium sources, including those associated with petroleum hydrocarbon-related developments (known as petro-lithium), where deep saline brine fluids in aquifers can be accessed via existing infrastructure or are co-produced within operating developments. Brine production volumes can vary significantly depending on the geological formation type associated with the hydrocarbon development, the production methodologies used to access the resources, and the age of the related developments.

In accessing these hydrocarbon resources, hydraulic fracturing of geologic formations has become a standard operational method utilized to increase a wells' productivity. Hydraulic fracturing is the action of pumping a fluid mixture, comprised primarily of water, a sand proppant material and some chemical additives, under high pressure to artificially fracture the formation and improve the overall production of natural gas and petroleum hydrocarbon liquids to the wellbore (Canadian Association of Petroleum Producers, 2019). Coupled with horizontal drilling practices, the application of multi-stage fracturing of a wellbore performed on multi-well pads has enabled the development of tight oil and gas reserves.

Though the quantity of water, sand, and additives and the type of additives utilized in these hydraulic fracturing operations can vary among different producers and geologic formations, some amount of FPW is produced during operations in conjunction with the targeted petroleum hydrocarbons. In the Duvernay shale, located near Fox Creek, Alberta, the average volume of hydraulically injected fluid per well has increased from approximately 36,000 m^3 in 2015 to 54,000 m^3 in 2018 (BOE Report, 2019). Goss et al. (2015) estimate that up to 50,000 m^3 of FPW is produced per well over its lifetime of production. While over the lifespan of a Montney development, approximately two-thirds of the fluid volume utilized for fracturing operations is returned.

Herein, it is imperative to differentiate between flowback water and produced water. Generally, flowback waters are considered a return of the fluids which were injected as part of the hydraulic fracturing process. In contrast, produced waters are fluids sourced from or interact with the geologic formation due to the production of the associated hydrocarbons (Stringfellow et al., 2014). Practically, some of the hydraulically injected fluids will be retained within the formation indefinitely, whereas the remainder will inevitably mix with the formation water, or dissolve minerals from the formation itself. Thus, there is no clear distinction between when flowback water ends and produced water begins. It is more suitable to generally define the high-volume water flows produced during the initial well production as flowback water, and the lower-volume water flows produced over the longer term are defined as produced waters (Stringfellow et al., 2014).

During standard production operations, FPW fluids and the associated gas and liquid petroleum hydrocarbons are conveyed to the surface through the individual wellbores and are transported to centralized facilities for separation and processing. In certain production operations, wellsite-based facilities are employed to measure and separate the different product phases, liquid from gaseous, and petroleum hydrocarbons from water, before being transported to the centralized facilities.

Due to the complex chemical composition of the FPW, including high total dissolved solids (TDS) contents, the fluids' storage and management practices are critical throughout their lifecycle. FPW can be characterized by extremely high contents of TDS exceeding 170,000 mg/L (Seip et al., 2021), and include various organic and inorganic constituents (Flynn et al., 2019). As such, any release of fluids into the environment would be expected to cause long-term environmental impact. Generally, the FPW life cycle consists of short-term containment and storage, which allows for potential reuse in subsequent hydraulic fracturing operations, and eventual deep well injection disposal as wastewater.

2.4.3.1. Lithium from Flowback and Produced Water in the Fox Creek, Alberta Region

The Alberta Energy Regulator (formerly the Energy Resource Conservation Board, ERCB) commissioned a study within the province of Alberta to establish geographic areas and geologic formations that have elevated lithium concentrations in the formation brines (Eccles & Berhane, 2011). The results of this study are illustrated in Figure 11. The study determined that within the Fox Creek, Alberta region, some deep geologic formation waters have consistently elevated lithium concentrations compared with fresh water, exceeding 75 mg/L and up to a maximum of 140 mg/L. These concentrations are on the lower end compared to the brine fluids identified in Table 3, but are significantly higher than natural environment concentrations.

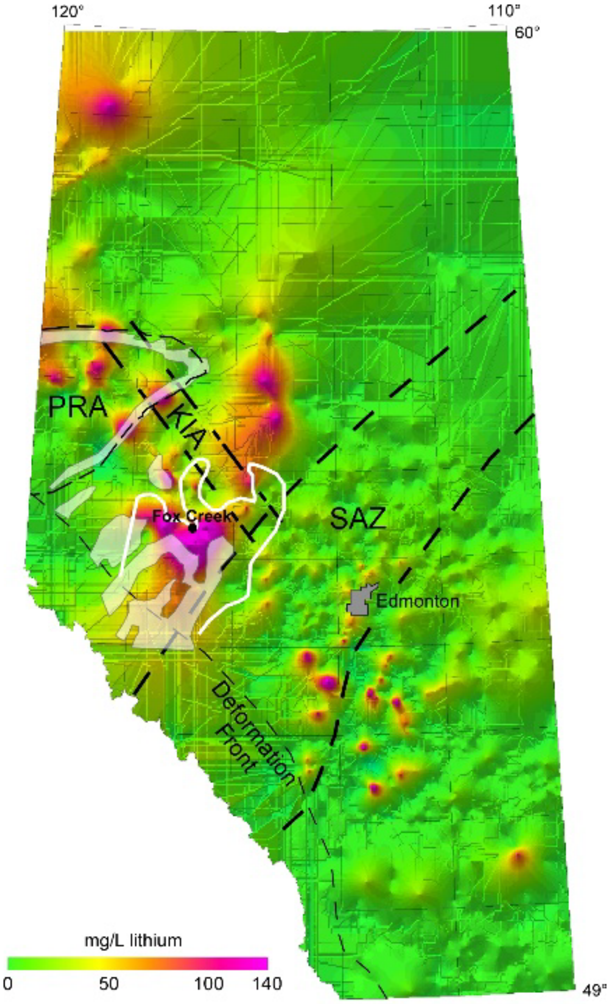

Figure 11. A general heat map of lithium concentrations in formation waters in Alberta (Eccles & Berhane, 2011).

From a geological perspective, Eccles & Berhane (2011) indicated that formation waters containing elevated lithium concentrations appear to be associated with the Leduc

Formation of the Woodbend Group and the Swan Hills Formation of the Beaverhill Lake Group.

With the large-scale development of the Duvernay Shale reservoirs beginning in 2011 (National Energy Board, 2017), there was a source of brine fluids (as FPW) from the Duvernay Formation that was concurrently deposited with the Leduc formation. Some of these newly encountered FPW fluids exhibited moderate concentrations of lithium. Seip et al. (2021) reported 43 mg/L of lithium in a field-collected FPW sample from the Duvernay Formation near Fox Creek, Alberta. More recently, water chemistry analyses of over 100 FPW samples collected from the Duvernay shale operations in Fox Creek of Alberta (Figure 12) give a reported lithium concentration range of 17–79 mg/L, with an average of 45.1 mg/L (Kingston et al., 2023). In both studies, magnesium ion concentrations from the Duvernay FPW samples exceeded 570 mg/L, resulting in the corresponding Mg/Li ion ratio higher than the recommended 6:1 ratio for lithium recovery using solar evaporative and precipitation methods (An et al., 2012 & Liu et al., 2020).

Eccles & Berhane (2011) hypothesized that the lithium contained within the deeper Devonian Beaverhill Lake and Swan Hills Formation waters resulted from hydrothermal activity and suitable tectonic features that allowed for the migration of lithium from the basement materials into the overlying formations. The relative proximity placement of the Duvernay shale formation in relation to the Swan Hills Formation or the Beaverhill Lake Group can vary depending on the specific geographic location being examined (Figure 12). Development activities within the Fox Creek region of Alberta, however, have indicated that formation pressures and pore fluids of Duvernay shale are hydraulically distinct from those of the underlying formations (R. Sunder, personal communication, August 26, 2021). It is speculated that the lithium within the Duvernay shale originates from the accumulation of Li^+ from the seawater within the marine sediments in which the shale was originally formed. Further, the source of the lithium within the Duvernay Shale FPW is potentially a result of the interaction between the hydraulically injected water, the formation fluids, and the sedimentary shale itself, resulting in the dissolution of lithium into the produced waters (Eccles, 2016).

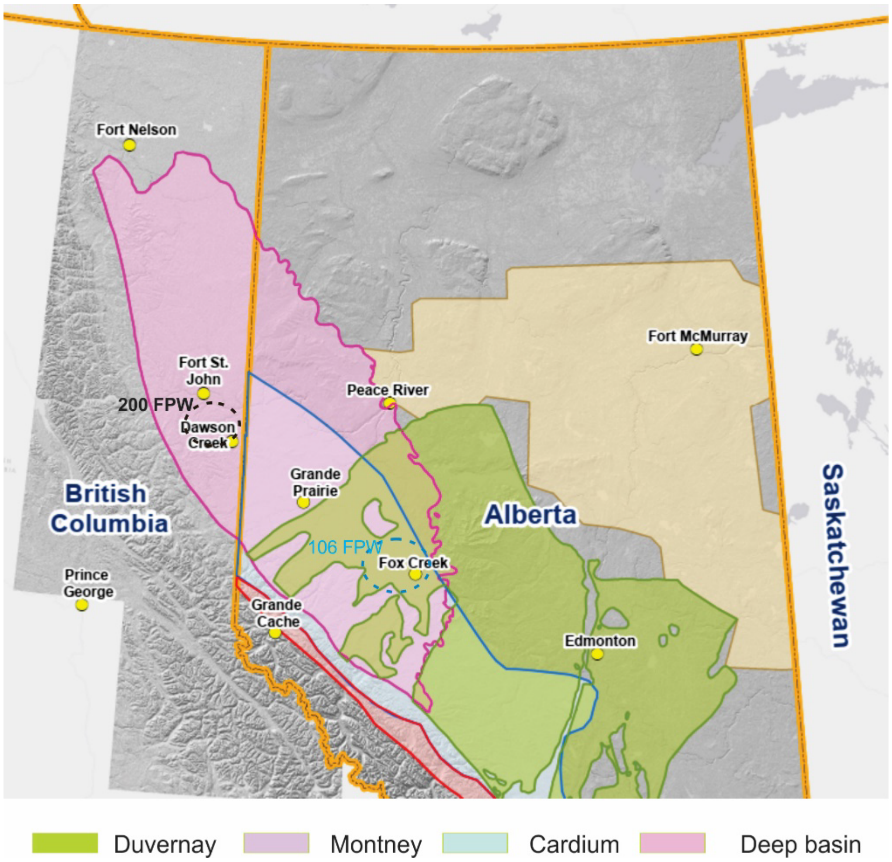

Figure 12. Locations of flowback and produced water (FPW) samples from the Duvernay (106) and Montney (200) formations discussed in this work.

2.4.3.2. Lithium from Flowback and Produced Water in Northeast B.C. Montney Region

At the time of this study, there is an ongoing and relatively widespread critical minerals investigation commissioned by Geoscience B.C., in partnership with the Geological Survey of Canada, aimed at systematically assessing the brine lithium resources in a variety of geological formations including the Montney Formation within northeast B.C. Concurrently, analytical results from over 200 previously collected FPW samples from Montney tight reservoir operations in the Dawson Creek area (Figure 12) indicate a lithium content range of 10–80 mg/L, with an average of 57.7 mg/L (Jiang et al., 2021, 2023).

2.4.3.3. Lithium from Flowback and Produced Water Closure

Given the large-scale collection and storage of FPW fluids at centralized Duvernay and Montney unconventional oil and gas development processing facilities, and the detection of elevated contents of lithium within these fluids, there appears to be significant potential in exploring this as a new lithium resource in Canada. This study builds on this knowledge base to assess the potential opportunity for the development of lithium resources in the large volume of FPW that is generally disposed of as wastewater at the present. By taking into account the physical and chemical properties of larger datasets of FPW samples, an evaluation of various DLE technologies developed for low-grade lithium brines are considered.

2.5. Direct Lithium Extraction

2.5.1. DLE Technologies

As discussed previously, lithium production through solar evaporation and precipitation is applicable within regions of high solar irradiation and low precipitation, and with source brines containing low relative concentrations of magnesium. This, however, is not a viable option for lithium production from FPW brine of the Duvernay shale reservoir in Fox Creek, Alberta or the Montney formation tight sandstone reservoirs in Northeast B.C., primarily due to the temperate climate conditions, low lithium contents, and high Mg/Li ratios. As such, alternative lithium extraction methods must be explored.

DLE methods, including solvent-based, membrane and nanofiltration-based, electrochemical-based, and adsorption/ion exchange-based methodologies, or a combination of these, have the potential to support lithium extraction from deep aquifer brine fluids including those from oil and gas operations.

2.5.2. Solvent-Based Lithium Extraction

Solvent-based extraction systems have been considered an effective approach for the recovery of a variety of metal ions in solution as the process is relatively simple and cost-effective under the proper conditions (Yang et al., 2019). The process is most commonly utilized within the hard rock mineral leaching process. As it applies to lithium extraction from brines, an insoluble organic liquid with an affinity for metal cations is mixed with the lithium source brine and a diluent to reduce the viscosity of the blended solution (Zhou et al., 2020). The lithium and other competing cations present are extracted from the brine solution and dissolved within the solvent solution. The (organic) solvent phase is then separated from the source brine, and the metal ions captured by the solvent can thereafter be extracted utilizing various washing and stripping agents (Zhou et al., 2020).

Oil and gas wastewaters contain significantly lower concentrations of lithium than the brines contained within the South American salars, and the former also contain high concentrations of competing cations and very high TDS. Therefore, selective extraction of lithium from oilfield brines through the use of solvents remains problematic. A recent study by Jang et al., (2017) utilized a solvent-based extraction process for lithium contained within synthetically produced oil and gas wastewater with cation concentrations of Ca^{2+} at 12,710 mg/L, Na^{+} of 29,780 mg/L, Mg^{2+} of 947 mg/L and Li^{+} of 106 mg/L. They determined there was a higher affinity for the extraction of Ca^{2+} and Mg^{2+} cations than that of Li^{+} cations. Utilizing a two-stage extraction process, with the first stage being designed to remove the competing cations Ca^{2+}, Mg^{2+}, Sr^{2+}, and Ba^{2+}, and the second stage designed for lithium recovery, the maximum extraction efficiency of lithium was determined to be 41.2% (Jang et al., 2017). Similarly, Zhou et al. (2020) conducted a solvent-based extraction on a simulated high magnesium salt lake brine with cation concentrations of Na^{+} at 1,840 mg/L, Mg^{2+} at 96,000 mg/L and Li^{+} at 350 mg/L, thus a Mg/Li ratio of 274. The maximum extraction efficiency of lithium from the simulated brine was determined to be 65.5% (Zhou et al., 2020).

Given the diverse nature of the various brine sources and the associated inorganic element concentrations, it is critical to select a suitable solvent for the lithium extraction process. Two solvents, di-(2-ethylhexyl) phosphoric acid (D2EHPA) and tributyl phosphate (TBP), have shown promise when coupled with complementary co-extraction agents (Jang et al., 2017; Zhou et al., 2020). Additional work with ionic liquids has achieved good lithium extraction efficiencies of >80%; however, they are impeded by low solvent recycling rates (Wang et al., 2018; Yang et al., 2019).

2.5.3. Selective Membrane and Nanofiltration Lithium Extraction

Membrane filtration systems are commonly utilized within municipal and industrial wastewater treatments and for producing freshwater from saline sources; however, their use in the extraction of lithium from brine sources is a relatively novel application (Swain, 2017). In the reverse osmosis process, water is forced through a partially permeable membrane under pressure, while the larger salt molecules are retained. For effective lithium extraction, the membranes or filters must be capable of selectively passing smaller monovalent ions (including Li^+), while retaining larger multivalent ions including Mg^{2+} (Bi et al., 2014).

There have been successful demonstrations of lithium extraction utilizing nanofiltration membranes on high Mg/Li brines, with very high rejection of Mg^{2+} of up to 96.1 %, and low rejection of Li^+ of 11.6% across the membranes (Xu et al., 2021). However, in the presence of other monovalent impurities including Na^+ and K^+ cations, a majority of the monovalent ions also pass through the membrane, thus requiring additional purification (Razmjou et al., 2019; Sun et al., 2015).

Further challenging the commercial use of nanofiltration membranes for lithium extraction from brine sources is the inherent rate, or volume flux achieved in the process. The rate at which the source brines can be processed and the energy required to do so can be considered prohibitive (Bano et al., 2015). Inherently, a significant volume of source water must be processed with brines containing low lithium concentrations.

Regarding their application to FPW fluids, pre-treatment processes to manage the organic impurities present in these brine fluids, including petroleum hydrocarbons must be considered. Organic materials contained within the source fluids will cause membrane fouling via pore blocking, plugging and clogging, as well as chemical degradation of the membrane materials, resulting in a reduced flux rate, and eventual filter replacement (Bano et al., 2015).

Advancements to nanofiltration membrane materials have increased the flux of the membranes while also increasing the rejection efficiency of multi-valent ions, and concurrently decreasing the rejection of the Li^+ ions (Razmjou et al., 2019; Xu et al., 2021). However, these processes are still challenged by the need for pre-treatment processes to limit membrane fouling by organic contaminants. Additionally, the eluent brine may require additional purification due to the presence of other monovalent ions on the downstream end of the processes, pending the ion selectivity of the membrane itself.

2.5.4. Electrochemical Lithium Extraction

Selective lithium extraction via electrochemical methods can be similarly compared to the recharging operations of LIBs, where the source of lithium is from the introduced brine solution.

The most straightforward electrochemical system is where a negative current is applied from an inert anode to a selective lithium-ion cathode, and the cations (including Li+) contained within the brine solution travel towards, and adhere to the cathode material (Zhao et al., 2019). Upon depleting the lithium from solution, or the saturation of the cathode with Li^+ ions, the source brine is replaced with a recovery fluid, and the current is reversed. This results in the Li^+ ions being released from the cathode material to create a lithium-enriched solution (Joo et al., 2020). Typical cathode materials utilized in the electrochemical extraction of lithium include lithium iron phosphate [$LiFePO_4$] (LFP), and lithium manganate [$LiMn_2O_4$] (LMO) (Joo et al., 2020; Zhao et al., 2019).

Advancements to the electrochemical cell design, the use of advanced membrane materials as separators, modifications to electrode materials, and continuous cycle operations have improved the efficiencies of lithium recovery from source brines and improved the Li^+ purity in the recovery fluids (Liu et al., 2020; Zhao et al., 2019). Within magnesium-rich brines, research has shown high lithium recovery coupled with an approximate 99% reduction of the Mg^{2+} from the initial solution to the recovery solution is possible (Liu et al., 2020).

Although there have been documented successes in recovering lithium from brines utilizing electrochemical processes, significant issues could affect the applicability of this extraction method for FPW fluids from oil and natural gas production. Given that the system operates primarily under applied current, the constant energy demands required to operate the system and selectively extract the lithium are significant (Liu et al., 2020). Depending on the method used to generate the electricity, such as fossil fuel-based versus renewable energy-based, associated greenhouse gas emissions must be considered.

Additionally, the corrosivity and potential to deposit scales from the source FPW fluids is considered extreme given the high TDS, which is due primarily to the presence in solution of alkaline earth metals including calcium, magnesium, strontium and alkali metals including sodium and potassium (Jiang et al., 2021; Reid et al., 2021). These cations inhibit lithium uptake due to damage to, or the blocking of, the lithium sorption sites of the cathode materials (Kanoh et al., 1993; Zhao et al., 2019). Further, the lithium recovery rates and purity within the recovery solution degrade with source brines of increasing Na+ and K+ cation concentrations due to similar electro-migration patterns (Liu et al., 2020; Razmjou et al., 2019).

2.5.5. Selective Ion Exchange Adsorbents

Selective ion exchange sorbents have garnered significant attention for their use in the recovery of lithium from brine solutions with significant coexisting impurities, including Na^+, K^+, Mg^{2+}, Ca^{2+} (Xu et al., 2016). Fundamentally, these specialized adsorbents can selectively retain specific metal ions due to their unique chemical structure while not being affected by other impurities in the solution (Xu et al., 2016).

Known as ionic sieves, the adsorbent materials are created from precursor materials that include the specific metal ion of choice. The target metal ion is stripped from the precursor material before use, leaving a vacant ion site that can accommodate ions with radii smaller than or equal to that of the stripped metal ion (Xu et al., 2016). In the case of lithium-ion sieves (LISs), only lithium and hydrogen ions can attach to the vacant site because lithium ions have the smallest ionic radii of the metal ions and hydrogen, as a reactive non-metal, is the only ion with a smaller ionic radius (Xu et al., 2016). Essentially, all other ions with larger ionic radii cannot fit within the vacant ion site of the material.

A conceptual representation of the function of the lithium-ion sieves is illustrated in Figure 13. The process of lithium extraction via LIS is based on a pH-dependent ion exchange process. In the Li^+ desorption cycle (LIS(Li) to LIS(H)), Li^+ ions are exchanged with H^+ ions when introduced to an acidic solution such as hydrochloric (HCl) acid. The desorbed Li^+ ions form a lithium salt (e.g. LiCl) in the receiving or recovery solution (Xu et al., 2016).

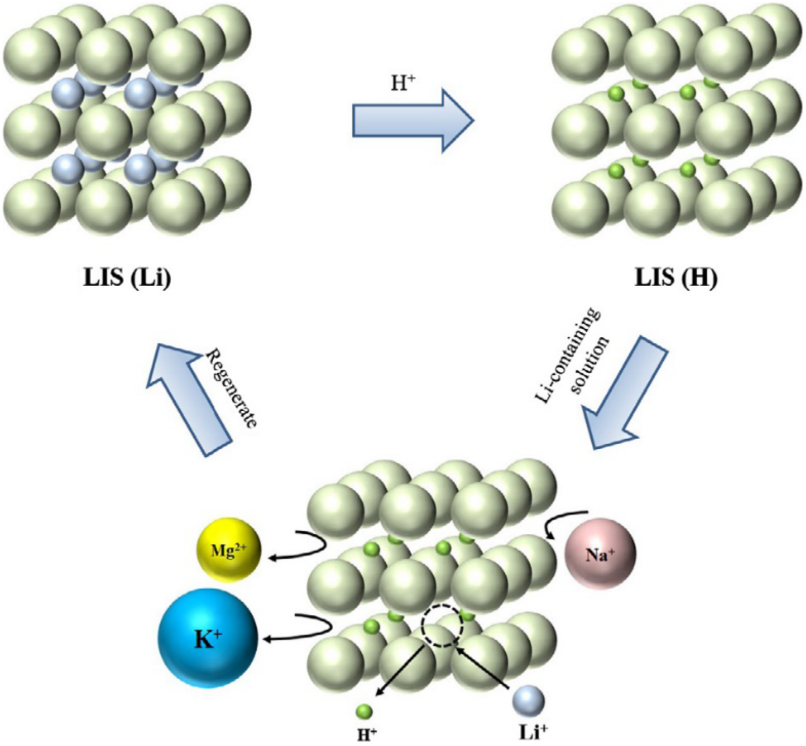

Figure 13. Conceptual model of a lithium-ion sieve process flow (Xu et al., 2016, reproduced with permission from Elsevier).

In the regenerative or uptake cycle, the LIS adsorbent materials are exposed to a Li^+-rich source solution. Due to the high affinity for Li^+ ions, the H^+ ions are desorbed into the receiving solution, with Li^+ ions sorbed into the material structure (Xu et al., 2016). Ions with larger radii, including Na^+ and K^+ are incapable of sorbing onto the material as a result of steric effects. Although the ionic radii of Li^+ and Mg^{2+} are similar, 0.060 nm and 0.065 nm, respectively (Nightingale, 1959), the Mg^{2+} ions do not adsorb into the structure because of a significantly higher energy requirement needed to enter the free ion-exchange site compared to lithium, thus inhibiting its uptake (Xu et al., 2016).

Given the extremely selective nature of the LISs, and the theoretically high rejection of other cations contained within lithium-bearing brines, these ion-exchange adsorbents have the potential for utilization within lithium-enriched oil and gas-produced brine fluids.

Two groups of LISs have shown significant promise in lithium extraction from saline brines. This includes lithium manganese oxide (LMO) and lithium titanium oxide (LTO) type adsorbents (Safari et al., 2020). LMO-based LISs have been demonstrated to have higher lithium uptake capacity and higher selectivity towards lithium ions. However, they tend to suffer greater sorbent losses when introducing acidic solutions in the desorption cycle (Jang & Chung, 2018; Xu et al., 2021). In comparison, LTO-based LISs benefit from lower sorbent losses during the Li^+ desorption process but suffer from lower total lithium uptake (Safari et al., 2020). A study by Jang & Chung (2018) employed an LTO-based adsorbent on synthetically manufactured produced water that matched the chemical profile of a field-collected shale gas FPW, with an Mg/Li ratio of 11. A lithium uptake of 58.3% was demonstrated across the adsorption-desorption process, while Mg^{2+} rejection in the effluent was 98.07% compared to the input solution (Jang & Chung, 2018). Seip et al. (2021) recently utilized an LMO-based LIS on an FPW sample from the Duvernay shale gas development near Fox Creek, Alberta. Lithium uptake of 80% and 98% was exhibited under optimal laboratory conditions for sorbents that contained precursor Li:Mn material ratios of 2:1 and 3:1, respectively (Seip et al., 2021).

While efficient uptake of Li^+ ions utilizing both LTO and LMO-based LISs has been documented in laboratory environments, several technical challenges must be addressed before the commercial utilization on lithium rich source brines, including

FPW. As discussed, LMO-based sorbents suffer from greater sorbent losses, more specifically, the loss of manganese into solution during the acid stripping treatments. This affects the sorbent structure and thus the Li^+ uptake rate (Xu et al., 2021). Recent advances in LMO materials design have resulted in improved sorbent structure integrity and performance by the fixation of cobalt (Qian et al., 2020) and aluminum (Chen et al., 2018) onto the sorbent material structure. Chen et al. (2018) reduced the dissolution of manganese materials from an LMO sorbent by 47% through the adherence of aluminum to the material structure, thus leading to improved lithium uptake after numerous cycling of the sorption-desorption process.

Both Total Suspended Solids (TSS) and organic compounds within FPW brines have also been shown to negatively affect the lithium adsorption efficiency of both LMO and LTO sorbents. In a study utilizing LTO-based adsorbent materials on synthetic shale gas FPW, lithium uptake was reduced by 25% when the average total organic carbon contained within the fluid concentration was increased by 100% between a field-collected brine and a synthesized brine fluid (Jang & Chung, 2019). Seip et al. (2021) also documented an 88% reduction in the uptake of Li^+ by an LMO sorbent material after one sorption-desorption cycle in the presence of 180 mg/L of dissolved organic carbon within the Duvernay Shale FPW. The authors originally hypothesized that the complex organic compounds of the FPW were chemically affecting the manganese materials, thus increasing sorbent losses. However, it was later confirmed that the organic compounds were also coating the sorbent materials, causing a reduction in Li^+ uptake (Seip et al., 2021). To minimize the negative chemical and physical effects on the LMO and LTO sorbents and improve the Li^+ recovery, novel wastewater pre-treatment processes to remove organic compounds from the lithium source brine must be applied (Jang & Chung, 2019; Seip et al., 2021).

Operationally, the efficiency of the Li^+ uptake and the rate at which the extraction from the source brine occurs are temperature dependent. Utilizing a synthetically produced lithium-enriched brine and an LTO-based sorbent, Wang et al. (2016) determined that there was a 63% increase in the rate of Li^+ uptake when the sorbent and brine solution temperature was increased from 30°C to 60°C. Seip et al. (2021) also determined that the maximum lithium uptake of the sorbents increased by 36% when the sorbent and source brine temperatures were increased from 20°C to 70°C. This can be attributed to the fact that the adsorption of the Li^+ on a LIS is an endothermic process requiring driving force energy. That is, at higher temperatures, the process becomes more thermodynamically favorable due to the increased energy content in the solution (Lawagon et al., 2016).

As LISs operate within a pH-dependent ion exchange process, the pH of the lithium source brine was also found to be a critical factor in the operational efficiency of the Li^+ uptake (Lawagon et al., 2016). In the uptake or regenerative process, the lithium uptake onto the sorbent materials releases the corresponding H^+ ion into the solution, thus resulting in a slight pH reduction. If the solution pH does not have the available pH buffer to counter the H^+ ion addition, then additional uptake of Li^+ is inhibited. Qian et al. (2020) and Seip et al. (2021) determined that lithium source brines with pH greater than 8 exhibited significantly higher lithium uptake than those solutions with a pH of 7 or lower. A representation of the relationship between solution pH, the Li$^+$ adsorption amount (qLi$^+$), and the Li$^+$ concentration in a source solution for a LMO sorbent is presented in Figure 14. The upper plateau represents the maximum Li$^+$ uptake per mass of sorbent material which occurs at pH>6.

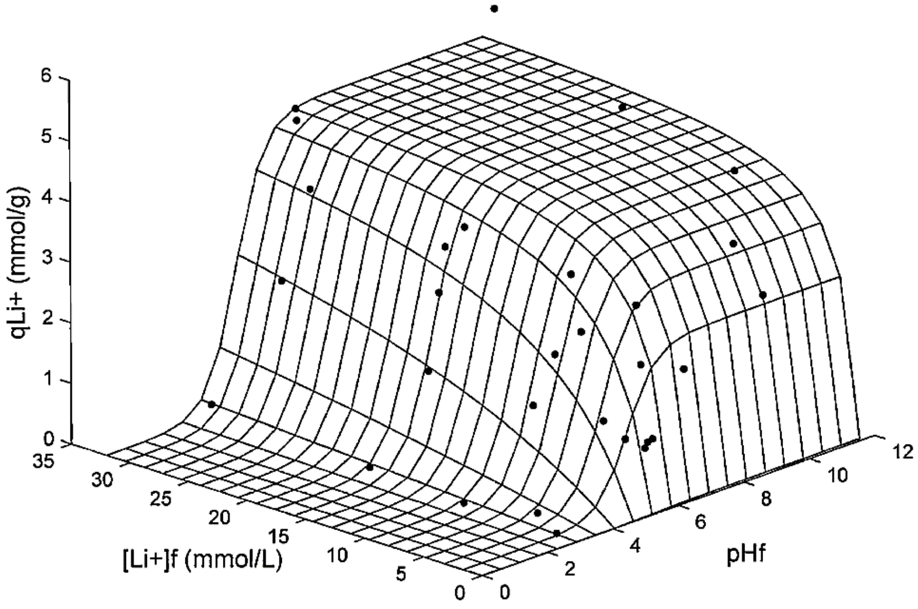

Figure 14. LMO-based sorbent uptake of Li+ and its relationship to the pH of feed brine (pHf) and initial Li concentration of the feed brine ([Li+]f) (Tian et al., 2010, reproduced with permission from Elsevier).

2.5.6. Direct Lithium Extraction Technologies Closure

Direct lithium extraction technologies have received significant attention due to the forecasted increases in lithium product demand, the environmental concerns associated with the traditional solar evaporative process and hard rock mining production, and the potential for resource development from alternative sources. Although these technologies are in their infancy, there has been significant research into overcoming some of the inherent challenges associated with lithium extraction from high TDS brine sources.

Improvements to material manufacturing and process optimizations could establish the potential for lithium extraction from oilfield brines, including FPW fluids and other alternative brine sources. Direct lithium extraction utilizing selective ion-exchange adsorbents, selective membrane filtration with electrochemical enhancements, or a combination of several DLE processes have shown the potential for use in lithium-bearing brines associated with co-produced FPW from oil and natural gas developments.

Considering the operating conditions associated with oil and gas-related FPW fluids, the feedstock properties for a lithium extraction process must be well understood. Optimizing the source (or feed) fluid physical and chemical conditions to maximize the rate and quantity of lithium uptake within each cycle will inevitably incur additional operating costs. Thus, a balance between the extraction (and impurity rejection) efficiencies and the economics of the entire system must be understood.

2.6. Lithium Refining to Saleable Commercial Products

The extraction of lithium from fluids via direct lithium extraction is the first step in developing a saleable lithium chemical. The initial product from the DLE process is typically a concentrated lithium salt as Lithium Chloride (LiCl) or Lithium Sulfate (Li_2SO_4), ranging from 1.4% (MacMillan et al., 2021) to 5% (Worley, 2019) lithium content. Additional purification by a stepped chemical precipitation process begins with the addition of sodium hydroxide or lithium hydroxide. Promoting the precipitation of carryover monovalent and divalent ions, particularly Mg^{2+} and Ca^{2+}, increases the solution's purity (Linneen et al. 2019). The contaminant precipitation is followed by filtration to remove impurities, including hydroxides and carbonates, further purifying the product to achieve the desired usable product. Applying reverse osmosis, evaporation and re-dissolution, secondary ion exchange, or any combination of these processes can further concentrate and polishes the LiCl or Li_2SO_4 products to a desired concentration.

The most common lithium products are lithium chloride (LiCl), lithium carbonate (Li_2CO_3) and lithium hydroxide monohydrate ($LiOH \cdot H_2O$). These products can be divided into technical-grade products and battery-grade products. Technical-grade materials, typically 95-99% pure lithium, are produced for industrial applications, including glass, ceramics, and grease manufacturing. They require less energy and materials to produce but collect a lower market value than their battery-grade counterparts. For battery-grade products, the acceptable levels of impurities within the product differ between off-taker and manufacturer and product types. However, for reference, greater than 99.5% purity is commonly cited as a baseline battery grade (Berry & Grant, 2019). It should, however, be noted that there is no official universal standard.

Additional refining is necessary to produce a battery-usable material from the lithium salt concentrate. In the production of Li_2CO_3 materials, a soda ash (Na_2CO_3) solution is mixed with the lithium concentrate to precipitate out the lithium carbonate material. This material subsequently undergoes additional filtering, washing and drying processes to create the final usable product (Worley, 2019). To produce $LiOH \cdot H_2O$ materials, the Li_2CO_3 materials can be re-dissolved in de-ionized water and mixed with hydrated lime ($Ca(OH)_2$) to create LiOH. After an evaporative crystallization process, a purified

LiOH·H2O material is produced. As an alternative to the chemical-driven process, a membrane-based electrolysis process can be employed with ultra-pure water to create the LiOH precursor material. Membrane electrolysis involves restricting hydroxide movement while permitting the free movement of lithium. This product then undergoes additional filtering, washing and drying processes to create the final $LiOH \cdot H_2O$ product (MacMillan et al., 2021).

It should be noted that the production of lithium carbonate material is considered a chemical reagent-driven process. In contrast, the production of lithium hydroxide monohydrate material can be either an electrical energy-driven process or a chemical reagent-driven process.

Chapter 3. Methodology

This study has examined the potential technical challenges associated with lithium extraction from oil and gas FPW fluid in a co-production scenario. From this, an economic evaluation of the development potential is conducted. Although lithium production from brines in Western Canada is a nascent industry, it has the potential for significant growth. However, in comparison to other global resources, there are unique challenges that require specific knowledge and expertise. Generally, lithium concentrations of Western Canadian FPW brines are significantly lower than lithium brines of the South American salars. Understanding lithium supply costs and the risks associated with lithium development is critical to understanding the potential of oil and gas operations supporting the domestic development of lithium resources.

3.1. Data Analysis - Methodology

Two unconventional oil and gas development areas were selected for this research: the Duvernay Shale development near Fox Creek, Alberta, and the Montney tight reservoir development near Dawson Creek, northeast British Columbia. These geologic developments are of particular interest due to their ongoing activity expected in the future.

This study evaluated the concentrations of dissolved lithium from a large set of Duvernay and Montney formation flowback produced water samples, which were contributed by select producers in the regions. The analytical results were generated at the Geological Survey of Canada (Calgary, Alberta). The chemical and physical properties of the FPW samples were also evaluated to help develop an understanding of the potential operational challenges for developing a lithium resource.

FPW samples were collected either directly from individual producing wellheads or at specific centralized facilities where FPW is gathered, processed, and stored alongside the target oil and natural gas. Production information, including well-specific volumes, centralized facility processing and disposal volumes, and fluid temperatures of the FPW at the centralized facility are collected and utilized for this assessment. The operating details from a specific processing facility located within the Fox Creek Duvernay operating area are used to define a typical facility in the Fox Creek Duvernay region and the B.C. Montney region. This study uses statistical analysis of the FPW analytical results and the associated brine volumes processed daily and annually to determine the potential lithium resource in the Duvernay FPW at a typical centralized facility. From this, a hypothetical facility in northeast B.C. with similar attributes to the Duvernay facility is created to understand the potential lithium resource of Montney FPW. Information obtained from the Duvernay facility was applied in the analysis of both the Duvernay and Montney-based analytical results and the subsequent determination of the lithium production potential for each. The physical and chemical parameters of the FPW that are identified as having a significant influence on project economics for this research are provided in Table 4.

Temporal trends of the physical and chemical characteristics of the FPW are identified by cross-referencing water sample collection dates with the status history of each associated well. Where well status information was not available from the producers, both the Alberta Energy Regulator (AER) and the British Columbia Oil and Gas Commission (BC OGC) maintain publicly accessible well databases containing information related to the history and status of petroleum hydrocarbon wells. For example, when natural gas or conventional oil wells begin officially producing, the AER defines the well status as either “Flowing” or “Pumping” depending on the well type. Herein, the change in well status to “Flowing” is defined as Day 0 from a temporal perspective. Thus, the number of days between the flowing date and the sample date is the differential utilized to define any temporal variations of the lithium concentrations.

Table 4: FPW physical and chemical parameters of significance for lithium extraction

Physical Parameters			
pH	Temperature	Total Dissolved Solids (TDS)	
Water Chemistry Parameters			
Boron (B)	Bicarbonate (HCO_3)	Calcium (Ca)	Chloride (Cl)
Lithium (Li)	Magnesium (Mg)	Potassium (K)	Sodium (Na)
Sulfate (SO_4)	H_2S	Organic matter (TOC)	

When characterizing the FPW volumes managed at the select Duvernay facility, the daily FPW production volumes conveyed to the centralized processing facility are compared to the disposal injection volumes at the facility to understand any differential in handling volumes or surcharge volumes. Herein, the disposal injection volumes are utilized in the quantification of the lithium resource, as any excess FPW production volumes would be subsequently handled and disposed of by third parties at separate waste disposal facilities (J. Small, personal communication, June 19, 2021).

From this, a Base Case project scenario is developed by combining the physical and chemical properties of the analyzed FPW with the operational characteristics of the select centralized processing facility. By analyzing this information, a comparison can be made with other brine-based lithium extraction and production projects, thus enabling the development of the economic model presented in this study.

3.2. Economic Modelling - Methodology

The inputs for the Base Case economic model, are presented in Table 5. Other income and cost factors that influence the outputs of this economic assessment are presented in Table 6. These factors are identified from available literature and subsequently assessed for their sensitivity to the economic results of the project scenarios. Unless otherwise identified, all measures of currency are presented in United States Dollars, and presented as $ or USD. Where the measure of currency is in Canadian Dollars, it is presented as C$ or CAD and is done so intentionally as the source data is provided as such. In all cases, the revenue or costs are converted to USD for the assessment. The foreign exchange rate assumed for this study is 0.75 CAD:USD. A step-by-step summary of the methodology and approach of the economic model and DCF analysis with supporting formulas are presented in Appendix A.

Table 5: Base Case economic model inputs

Project Scenario[1]	**Discount Rate**	**Jurisdictional Multiplier**	**Effective Average Tax Rate**	**Electricity Cost (C$/KWh)[2]**	**Royalty Pre-Payout (Gross Revenue)**	**Royalty Post-Payout (Net Revenue)**
Duvernay (AB)	12%	1.00	23%	0.11	1%	12%
Montney (B.C.)	12%	0.93	27%	0.075	2%	13%

[1] All projects are assumed to have a 20-year life.

[2] Presented as $CDN from available sources. Converted to $USD within the economic assessment.

A Discounted Cash Flow (DCF) analysis was conducted for several project scenarios. The output responses of the DCF model include Before and After Tax and Royalties Supply Costs (Discounted), Discounted Payback Period, Internal Rate of Return (IRR), Profitability Index and Net Present Value (NPV). The DCF analysis results can be used to better understand and compare the investment value between project scenarios and can help identify a project with higher potential return to a developer. Simply, in a project DCF analysis the total value of a project over its life is estimated by determining the present value of all current and future cash flows, including expenses and revenues, with a discount rate equal to an assumed weighted average cost of capital for a developer considering the project investment. Given the early stage of DLE technology and the infancy of lithium development in Western Canada, a discount rate of 12% was selected for this assessment to represent a more realistic higher-risk development approach (A. Fogwill, personal communication, August 26, 2021). Amongst a group of potential project scenarios, the project with a higher IRR, higher profitability index, and higher NPV will have a lower payback period, and will thus be a higher valued project to a developer or investor.

Table 6: General project economic factors

Project Income	**Project Expenses**
Lithium Product Pricing	Capital Cost / Capital Intensity Ratio
Lithium Concentration	Operation and Maintenance Costs Expenses
Lithium Recovery Rate	

Given the jurisdictional differences of the Base Case project scenarios, the Duvernay in Alberta and the Montney in British Columbia, the distinct tax and royalty regimes were considered for this analysis. Therefore, the analysis included after-tax and royalty output values from the DCF model across the various jurisdictions. The royalty rates applied within this economic assessment were based on a *Comparative Review of the Rate of Royalty in the Canada Mining Regulation* (The Mining Association of Canada, 2008) which includes both Alberta and British Columbia jurisdictions. Further, provincial capital cost multipliers were utilized to depict the variations in capital costs between the different provinces. These provincial capital cost multipliers for each province take into consideration the share of various capital cost elements (such as labor, materials, and equipment) and their differences across different provinces (Doluweera et al., 2020).

The DCF model also places significant importance on the prevailing and projected market prices for lithium chemicals. Significant fluctuations and notable differentials between the commodity prices of LHM and LC materials have occurred in the last decade, with a significant increase in spot pricing since 2021, as presented in Figure 15. Although lithium battery chemical pricing remained relatively stable from 2017 through to early 2021, there was an approximate 300% increase in spot pricing costs into early 2022. Generally, $LiOH \cdot H_2O$ pricing has maintained an approximate $5,000 USD per tonne premium over Li_2CO_3 products.

3.2.1. Supply Chain Description

Herein, the extent of this assessment is limited to the extraction of raw lithium material from the co-produced FPW utilizing ion exchange based direct lithium extraction systems, and the subsequent concentration, purification and production of the end-use lithium product as either technical grade LC or LHM (reported as units of LCE). It is assumed that the lithium end product would be transported to a port on the west coast of Canada where it will be subsequently shipped to existing offshore battery manufacturers; alternatively, the product could be transported in bulk to a recently announced battery manufacturing facility to be located in Windsor, Ontario, with a commissioning date not yet confirmed (La Grassa, 2022), or to other similar infrastructure in North America.

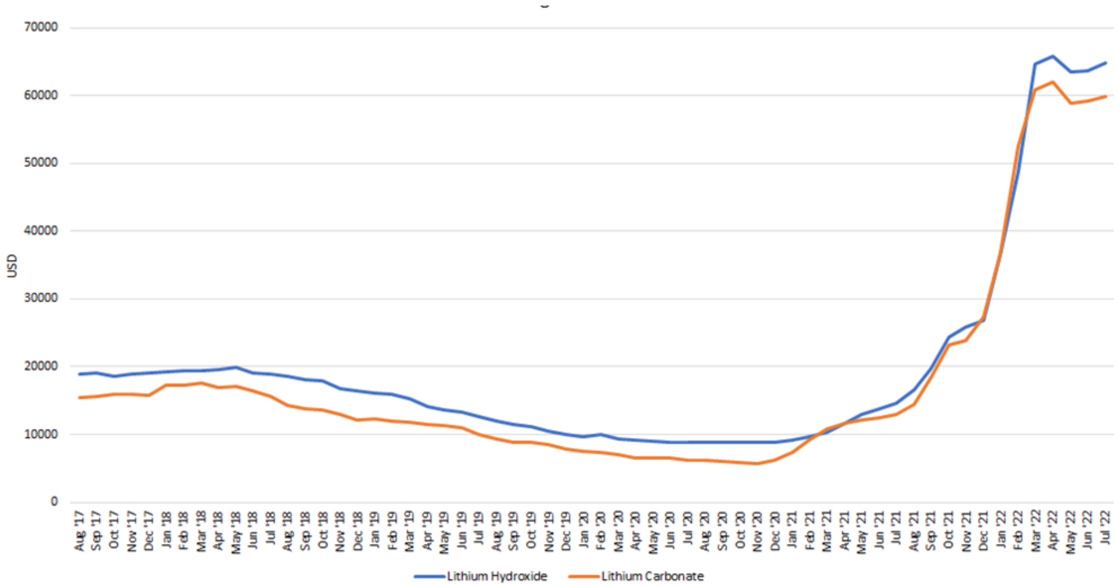

Figure 15. Lithium battery chemical pricing (based on data from Roskill Information Services Ltd., 2021b). Unit pricing as USD per tonne of battery grade chemical. Grades of lithium carbonate >99.5% Li_2CO_3, and Lithium hydroxide monohydrate >56.5% LiOH.

3.2.2. Reference Scenario Descriptions – Capital and Operating Costs

In developing an understanding of the capital and operating costs associated with the hypothetical Base Case lithium extraction project scenarios, reference information from National Instrument 43-101, Standards of Disclosure for Mineral Projects reports for proposed brine-based lithium developments was utilized. Key features and characteristics of these operations (hereafter the Reference Scenarios) are presented in Table 7 and used in the development of the Base Case project scenario capital and operating costs for this assessment. Reference Scenario #1 is described as a proposed lithium extraction and processing facility whose primary and only goal is the production of battery-grade LHM from brine fluids utilizing an ion-exchange extraction process on a currently undeveloped site with little to no existing associated infrastructure (MacMillan et al., 2021). Reference Scenario #1 is identified as E3 Lithium's Clearwater Lithium Project situated in Central Alberta, Canada.

Table 7: Key features of representative lithium project Reference Scenarios

	Total Capital Expenses ($USD MM)	**Design Brine Input Rate m^3/day**	**Average Li^+ Brine Grade (mg/L)**	**Design Production (T/year) [T/yr LCE]**	**Capital Expense Intensity Ratio ($USD/tonne annual production)**	**OPEX Unit Rate ($USD/tonne produced)**	**Project Life**
Reference Scenario #1[1]	602.0	140,000	74.6	20,015 LHM [17,566 LCE]	30,077	3,656	20 yrs
Reference Scenario #2[2]	437.2	67,696	168	20,900 LC [20,900 LCE]	20,919	4,319	25 yrs

Adapted from [1]MacMillan et al., 2021; and [2]Worley, 2019.

Reference Scenario #2, in comparison, is described as a proposed lithium extraction and processing facility with existing primary production of brine-based bromine chemicals, and a proposed secondary goal of co-producing battery grade LC from the spent brine utilizing an ion exchange extraction process on an existing and developed site with significant existing associated infrastructure (Worley, 2019). Reference Scenario #2 is identified as Standard Lithium Ltd.'s Lanxess Project (Worley 2019) situated in Southern Arkansas U.S.A.

Lithium production from FPW from existing oil and gas production facilities would most closely align with Reference Scenario #2, given the secondary (or co-production) of lithium from an existing production stream. However, it was deemed relevant to also consider lithium from FPW in a primary production scenario for comparative purposes.

The economic assessment is based on three crucial assumptions, which serve as the foundation of the analysis. First, it is assumed that the capital infrastructure required to extract, purify and produce the lithium end product as described in the Reference Scenarios is scalable, such that there is a direct relationship between capital cost and the brine volume processed and the lithium mass produced. These unit costs can be represented by the capital expense intensity ratio (CIR), where the CIR is a metric of the capital costs per unit of production ($/m^3 of brine volume production or $/tonne of lithium mass production) on an annual basis. This costing assumption was used for developing the Base Case project scenario capital costs from the Reference Scenarios.

Second, there are select fixed Capital Expenses (CAPEX) for any lithium extraction and production project of any reasonable scale or size. Consequently, regardless of the production scale, whether in terms of volume or mass, smaller-scale projects will incur higher CIRs due to the fixed capital costs, when compared to larger-scale projects. The Reference Scenario cost assessments attempt to account for these fixed capital costs, such that the CIRs of a smaller development would be expected to be higher than that of a comparatively larger facility.

Third, lithium production from an individual centralized FPW production facility is expected to be on a significantly smaller scale than that of the identified Reference Scenarios. As such it is assumed that concerted efforts between producers within the Duvernay or Montney development areas would result in an area-based centralized lithium refining and production facility that would be of a relative total scale similar to that of the Reference Scenarios. As such, each of the Base Case project scenarios assessed in this study was assumed to supply a portion of the total amount of lithium feedstock into an area-based lithium refining and production facility, while also carrying the corresponding portion of the total capital costs. It is difficult to confirm if such a concerted effort is feasible, but for the sake of this assessment, the assumption allows for the development of a reasonable capital cost estimate.

3.2.3. Project Scenario #1 – Lithium Hydroxide Production

The following costing development information relates to the assessment of Reference Scenario #1 with the primary production of LHM materials from a brine source using ion-exchange DLE technology. Capital and operating costs from the reference scenario are assessed for applicability to the co-production scenario, modified and revised as deemed appropriate, and scaled to the Base Case project scenarios of the Duvernay and Montney.

3.2.3.1. Capital Cost Assumptions

The CAPEX costs of Reference Scenario #1 are examined for applicability in a co-production scenario. Any costs deemed redundant in a co-produced scenario are eliminated from the Reference Scenario #1 capital estimate to produce a revised CAPEX cost. Specifically, the CAPEX costs associated with the production and disposal of brine fluids, including wells, pumps, and pipeline infrastructure are removed for this assessment (MacMillan et al., 2021). This is justifiable given that in the Base Case project scenarios, FPW as the lithium source is co-produced within the existing hydrocarbon fluid production and storage infrastructure of the centralized petroleum hydrocarbon processing facility. Thus, under this premise any additional brine production infrastructure would not be required.

From the revised CAPEX cost estimate of Reference Scenario #1, specific processes and the associated costs are identified as either input-brine-volume driven or contained-lithium-mass driven. It is important to understand the distinction between the volumetric-based CAPEX cost and the mass-based CAPEX cost given that a comparable lithium production facility processing input brine with lower lithium concentrations would require a larger input of brine volume and thus incrementally larger front-end infrastructure to produce an equivalent contained-lithium-mass or output. On the other hand, the associated infrastructure required to purify, concentrate, crystallize, and produce an equivalent mass of lithium end product would remain comparatively the same. A general breakdown of the specific lithium production processes governed by input brine volume, or by contained lithium mass, is represented in Figure 16.

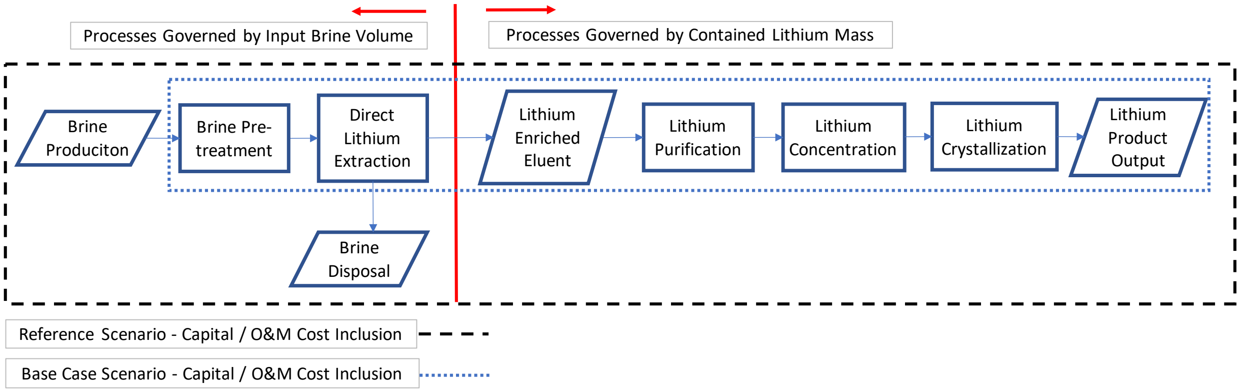

Figure 16. Diagram of Reference Scenario #1 process flow with the volume or mass-based costs indicated. Base Case Scenario costs do not include brine production or disposal as the Projects are identified as co-production from an existing production stream.

The process-allocated total CAPEX costs are converted to process-allocated specific CIRs based on Reference Scenario #1 features (Table 7) including input brine concentrations (thus volume) and annual production output. In turn, these process-specific reference CIRs are applied to the Base Case project scenarios (Duvernay or Montney) based on the FPW resource characterizations to account for the differences in input concentration and potential production output of lithium mass. This produces a weighted CIR specific to either of the Duvernay or Montney scenarios. A workflow diagram of this capital cost progression is represented in Figure 17.

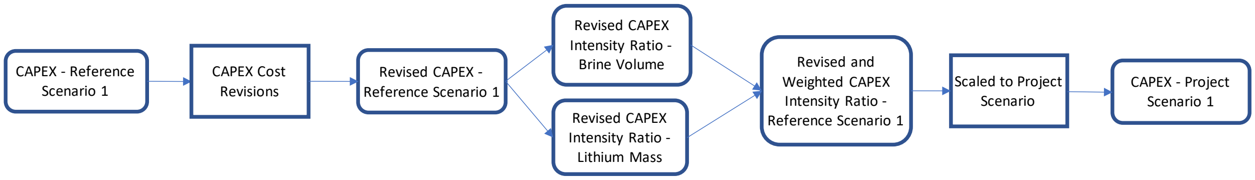

Figure 17. Project Scenario #1 CAPEX cost progression from Reference Scenario #1.

3.2.3.2. Operating Cost Assumptions

Similarly, the Operating Expense (OPEX) unit costs associated with Reference Scenario #1 are examined to eliminate or modify certain expenses to better reflect the characteristics of the Base Case project scenarios (Duvernay or Montney). Specifically, all electricity, operations, maintenance, and service costs associated with brine source wells, disposal wells, pumps, and pipeline infrastructure are deemed redundant and eliminated for the Base Case project scenarios, given that these activities occur under existing hydrocarbon production operations.

Through the assessment of operating cost components, the electrical energy demands required for the operation of the lithium extraction and production process systems are considered a crucial component (MacMillan et al., 2021; Worley, 2019). Based on

MacMillan et al. (2021), the electrical energy required to extract, process and refine a LHM product as a lithium primary facility, was 15,986 kWh/T of LHM (14,068 kWh/T LCE). For this assessment, commercial electrical rates are identified for each jurisdiction and assumed to be C$0.11 /kWh in Alberta (Duvernay), and C$0.075 /kWh in B.C. (Montney) (Doluweera et al., 2020).

Other OPEX cost sensitivities considered in the assessment include the management of the feedstock pH, fluid temperatures, TSS, and organic carbon content (TOC). From these inputs, revised OPEX unit costs ($OPEX/T LHM) were developed and applied to either of the Duvernay or Montney scenarios.

3.2.4. Project Scenario #2 – Lithium Carbonate Production

3.2.4.1. Capital Cost Assumptions

The Base Case Duvernay or Montney project scenarios and Reference Scenario #2 can be categorized as similar types of lithium production operations as they involve co-production (or secondary production) from an existing production stream. Reference Scenario #2 CAPEX costs are similarly examined to identify any redundant costs. Due to a lack of detail on the CAPEX cost components of Worley (2019), with no distinction between volumetric or mass-based process costs, the total CAPEX costs of Reference Scenario #2 were not reduced or modified.

The Reference Scenario #2 CAPEX cost estimate from Worley (2019) does, however, provide a distinction between the costs associated with the intermediate production of lithium chloride and the final production of LC. As such, distinct CIRs for the lithium chloride and LC processes were developed and scaled to the Duvernay or Montney Base Case project scenario that similarly accounts for input brine concentration to lithium chloride and output production of LC chemicals. From this, a weighted CIR was developed and applied to either the Duvernay or Montney scenarios. A workflow diagram of this capital progression is represented in Figure 18.

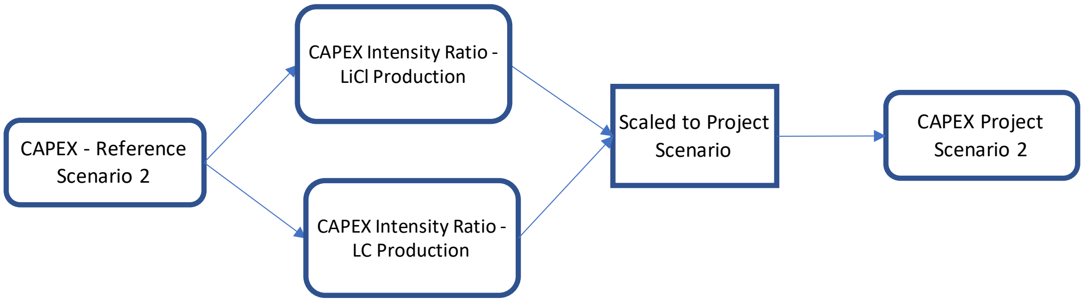

Figure 18. Project Scenario #2 CAPEX cost progression from Reference Scenario #2

3.2.4.2. Operating Cost Assumptions

The OPEX costs of Reference Scenario #2 are also examined to eliminate or modify certain operational expenses to better reflect the characteristics of the FPW and the defined Project Scenario. Electricity demand is again deemed a critical operational cost component. Based on Worley (2019), the electrical energy required to extract, process and refine a LC product via co-production was 8,212 kWh/T LCE. The difference in electrical intensity per unit of production is worth noting when compared to Reference Scenario #1, which requires 15,986 kWh/T LHM. This variation is a consequence of the secondary nature of production and the fact that LCE production is a chemically driven process, while LHM production is assumed to be an electrically driven process, as defined in Section 2.6.Commercial electrical rates were again applied based on the appropriate jurisdiction and assumed to be C$0.11 /kWh for Alberta, and C$0.075 /kWh in British Columbia (Doluweera et al., 2020).

Other OPEX cost sensitivities considered included the management of the feedstock brine pH, fluid temperatures, TSS, and organic matter, which were revised based on the FPW chemistry of the Base Case project scenarios (Duvernay or Montney). From these inputs, revised OPEX unit costs ($OPEX/T LCE) were developed and applied to either of the Duvernay or Montney scenarios.

3.2.5. Capital and Operating Cost Revisions – Closure

The CAPEX and OPEX estimate from Worley (2019) and MacMillan et al. (2021) are expected to be compliant with a Class 4 Estimate and Class 5 Estimate respectively, as defined by the American Association of Cost Engineers (AACE) International Recommended Practice No. 18R-97 Cost Estimate Classification System. As such, the accuracy of the reference cost estimations is expected to be -30% to +50%. Similarly, the cost estimates developed for this assessment are expected to be compliant with AACE R.P. No. 18R-97 as a capacity-factored, judgment-based estimate. As such the costing approach completed for this assessment would be expected to fall within the same range of accuracy as an AACE Class 5 estimate classification.

Upon determining the CAPEX and OPEX unit rates for each Base Case project scenario (Duvernay or Montney), a 15% contingency factor was added to each given the uncertainty associated with the assumptions made within this research. Jurisdictional multipliers were then applied to each Base Case project scenario to capture the variations in costs within different jurisdictions. A factor of 1.0 is applied to the Duvernay, Alberta-based scenarios, and a factor of 0.93 is applied to the Montney, B.C.-based scenarios (Doluweera et al., 2018).

Given that each of the reference scenarios produced a distinct product (e.g., LHM versus LC), individual DCF analyses are completed utilizing the revised CAPEX and OPEX costs for each Base Case project scenario. A summary of the scenarios is listed in Table 8 below.

Table 8: DCF scenarios summary

	Development Area	
Reference Scenario #1 (LHM product)	Duvernay Project Scenario #1	Montney Project Scenario #1
Reference Scenario #2 (LC product)	Duvernay Project Scenario #2	Montney Project Scenario #2

3.3. Project Revenues

Considering the project revenues, lithium product pricing is governed by external market forces. As discussed in Section 3.2, commodity pricing of LC and LHM battery-grade materials have fluctuated significantly in recent years. The specific commodity pricing inputs utilized in the DCF assessment are based on information from the reference scenarios (MacMillan et al., 2021; Worley, 2019) and more recent commodity forecasts. For this assessment, a moderate market-driven price scheme is developed. Base pricing for battery grade LC product was set at $25,000 USD per tonne LC, increasing to $35,000 USD per tonne by the year 2028, followed by price annual increases of 2% to account for inflation only. Base pricing for battery grade LHM product is set at $30,000 USD per tonne LHM, increasing to $40,000 USD per tonne by the year 2028, followed by price annual increases of 2% to account for inflation only. This base pricing scenario was selected as a moderately conservative approach, given the potential of a supply and demand gap based on discussions presented earlier in Section 2.2; however, it does not directly account for the most recent pricing increases that exceed $60,000 USD per tonne LHM and LC. A summary of the pricing assumptions of the lithium battery chemicals is presented in Appendix A.

Regarding resource production, the results of the FPW analytical data is used as feedstock lithium concentrations (Kingston et al., 2023), with consideration given to the temporal variations identified. Lithium recovery rates of the employed ion-exchange DLE technology were assumed to be 90% of input concentrations and were based on assessments of available academic literature and publicly available information.

3.4. Sensitivity Analysis

Based on the above established CAPEX and OPEX cost models and the baseline economic inputs, a sensitivity analyses of various factors is then performed to determine their effect on the DCF model outputs. In each case, a single variable is modified from the base scenario created, while all other variables are kept constant at their baseline levels. All variables are modified within a -/+ 25% range as shown in Table 9.

Table 9: Variables assessed in sensitivity analysis

Variable	**Sensitivity Range**
CAPEX	-25% to +25%
OPEX	-25% to +25%
Lithium concentration in brines	-25% to +25%

3.5. Investment Validity

In defining the economic success of a project scenario, consideration is given to the technology readiness level associated with DLE, and the state of the industry within the region of influence, specifically North America (Natural Resources Canada, 2020). According to publicly available information (BusinessWire, 2021; Worley, 2019), DLE technology readiness is best defined as Level 7 where “prototype is at planned operational level and is ready for demonstration in an operational environment. Activities include prototype field testing” (Government of Canada, 2018). In combination with the early stages of a potential lithium production industry within North America, early investors require a return on investment that offsets the potential risks. A threshold of 22% on the after-tax IRR was selected as a reasonable risk premium to define project success. From this IRR threshold, a 10% risk premium has been applied to the baseline discount rate as a reasonable justification for project validity.

Chapter 4. Analysis and Findings

4.1. FPW Data Assessment

The physical and chemical properties of the FPW from the provided samples are evaluated to quantify the lithium resource flowing through the select centralized facility of the Base Case project scenarios and for the identification of operational considerations and costs. Analytical results for 106 co-produced FPW samples from the Duvernay in the Fox Creek region of Alberta, and for 200 co-produced FPW samples from the Montney in the Dawson Creek region of northeast B.C. are assessed. A summary of the average results for the physical and chemical parameters of significance for the FPW are summarized alongside the Reference Scenario brines for comparison in Table 10.

Box and whisker plots are utilized in this assessment to visually present analytical data sets into respective statistical quartiles, averages and outliers. A box-and whisker plot present the distinct data sets, with indicators for minimum range, lower quartile, median, upper quartile, maximum range, and statistical outliers.

4.1.1. Fluid pH

As fluid pH was determined to be a critical parameter associated with the efficiency of the lithium extraction employing ion exchange processes, input fluid pHs are assessed where data were available. Brine pre-treatment to ensure input fluid pH is at near-neutral conditions (pH 7-8) is necessary to optimize lithium extraction uptake, as illustrated in Figure 14. A representation of the quartiles, median, and range of pH for both Duvernay and Montney FPW fluids is presented in Figure 19. The average fluid pH is 5.95 for the Duvernay FPW and 4.59 for the Montney FPW resources samples.

For reference, the feed brine of Reference Scenario #2 is highly acidic, with a pH of 1.03, thus requiring 1,039 kg of anhydrous ammonia per tonne of LC for brine pre-treatment to increase the pH to optimal conditions (Worley, 2019). Comparatively, the feed brine of Reference Scenario #1 is neutral, with a pH of 7, thus requiring 0.91 kg of sodium hydroxide per tonne of LHM produced to shift or maintain the fluid pH within optimal conditions (MacMillan et al., 2021). For this assessment, it is assumed that the quantity of chemical reagent required for pH pre-treatment is 15 kg of sodium hydroxide per tonne of LCE produced for both project scenarios.

Table 10: Summary of average brine physical and chemical properties of significance to direct lithium extraction

Project/Reference Scenarios		**Duvernay**	**B.C. Montney**	**Reference Scenario #1**	**Reference Scenario #2**
Brine type		Co-produced FPW	Co-produced FPW	Produced Brine	Co-produced Brine
Physical properties					
pH	pH	5.97	4.59	7	1.03
Temperature	°C	16.1	16.1	70	60.5
Chemical properties (dissolved)					
Barium (Ba)	mg/L	8.3	11.9	3.3	8.8
Bicarbonate (CO_3^-)	mg/L	48	N.D.	524	-
Boron (B)	mg/L	69	24.3	286	163
Calcium (Ca)	mg/L	11,983	17,547	23,574	34,793
Chloride (Cl)	mg/L	121,160	135,390	145,704	171,860
Lithium (Li)	mg/L	45.1	57.7	74.6	169
Magnesium (Mg)	mg/L	906	1,777	2,811	2,981
Potassium (K)	mg/L	1,716	2,253	6,372	2,265
Sodium (Na)	mg/L	56,771	65,438	49,453	66,480
Sulphate (SO_4)	mg/L	222	106.4	282	390
Total Dissolved Solids	mg/L	191,983	224,122	228,264	303,555

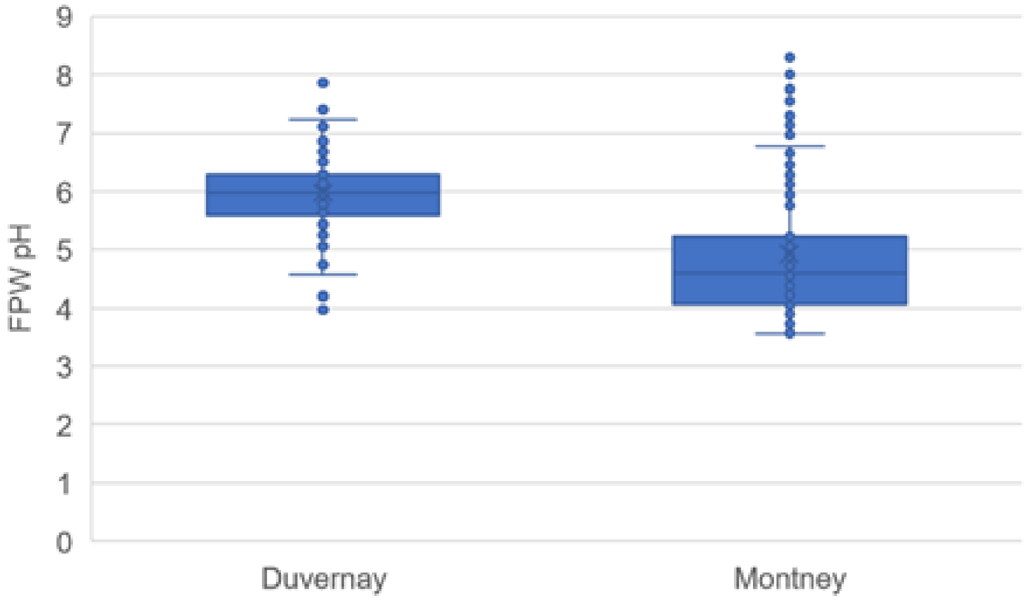

Figure 19. Range of FPW fluid pH. Average FPW fluid pH 5.97 for the Duvernay FPW (left) and 4.59 for the Montney FPW (right). Circular markers indicate the individual sample data points, while the box and whiskers represent the statistical quartiles of the data set.

4.1.2. Fluid Temperature

As the rate of lithium uptake within ion exchange systems was determined to be highly dependent on fluid temperatures, the range of FPW temperatures at the select centralized facility was verified. Based on information provided by the select producer, the average FPW fluid sample temperature at the centralized facility was determined to be 16.1°C (Figure 20), which is notably lower than the respective temperatures of the reference scenario fluids, and the optimum uptake conditions of greater than 60°C (Seip et al., 2021).

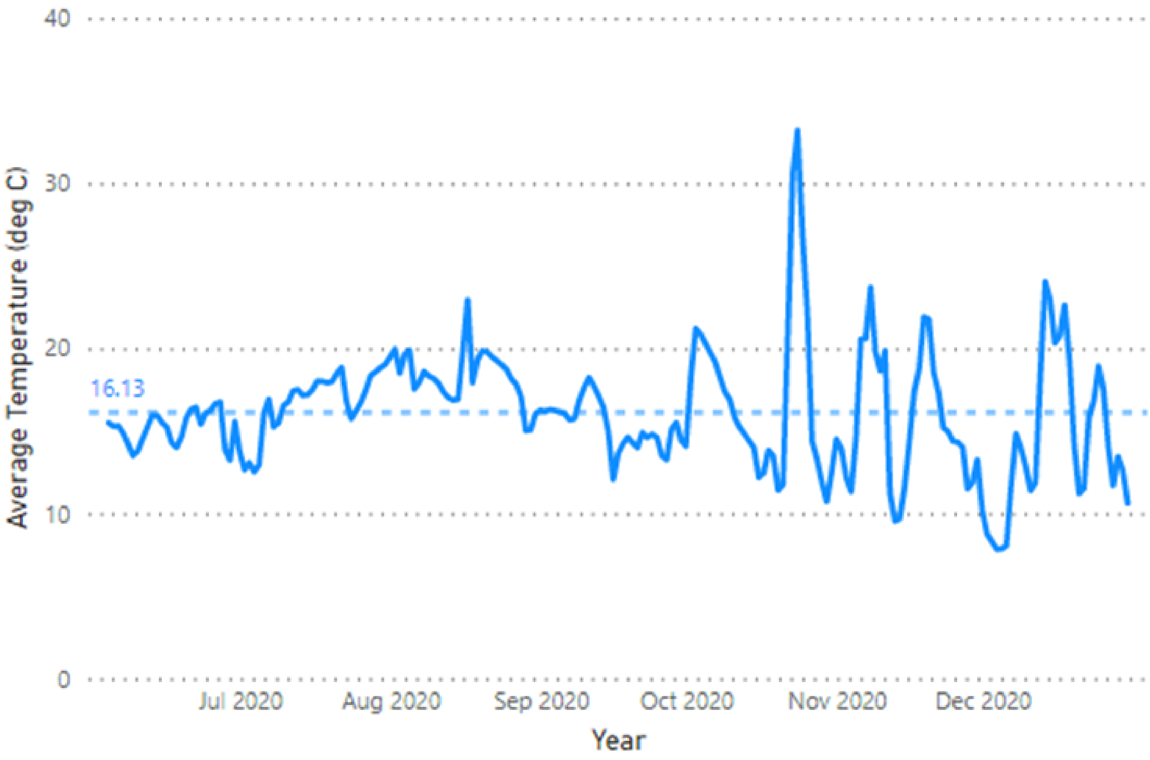

Figure 20. Average FPW fluid temperature at Centralized Facility. Average temperature used for Base Case Project Scenario FPW was 16.1°C.

To address this operational temperature deficit, it was assumed that a commercially available natural gas-fueled, industrial-sized water heater was utilized to increase the FPW temperature by 50°C from the baseline of 16.1°C. It was assumed that fuel (natural) gas was supplied by the centralized hydrocarbon production facility, with an associated cost of $1.50/BOE, which was determined to be the break-even OPEX cost of a typical natural gas processing facility (Tourmaline Oil Corp., 2021).

4.1.3. FPW Chemical Composition

Referring to Table 10, although there are notable differences in the concentrations of the major ions between the feed FPW fluids and the Reference Scenario brines, including Cl^-, Na^+, Ca^{2+}, Mg^{2+}, K^+, and TDS, all are on the scale of a hypersaline (i.e., >35 g/L of seawater) solution. While the rejection rate of ions for the ion exchange DLE process is known to exceed 98% in the lithium-enriched effluent, subsequent purification, filtration, and polishing process steps are still necessary to produce a high-quality battery-grade lithium product given the inlet TDS concentration.

4.1.4. Lithium Content

A representation of the quartiles, median, and range of lithium concentration data for the Duvernay and Montney FPW brine sources is presented in Figure 21. The average concentration of lithium of the Duvernay source FPW fluids is 45.1 mg/L, whereas the Montney source FPW averages 57.7 mg/L. For reference, the average lithium concentration of the Reference Scenario #1 brine is 74.6 mg/L, and the average lithium concentration of Reference Scenario #2 brine is 169 mg/L, significantly higher than those of both Duvernay and Montney FPW. The disparity in lithium concentration among the targeted brines in this study, compared to the Reference Scenario's, validates the utilization of both volume-based and mass-based CIRs. This approach is necessary since different volumes of brine need to be processed to produce the same mass of lithium. In both Base Case Duvernay and Montney project scenarios, the Mg/Li ratios exceed 20, indicating that the solar evaporative precipitation method for lithium recovery is not an effective or economic production method, regardless of the environmental conditions.

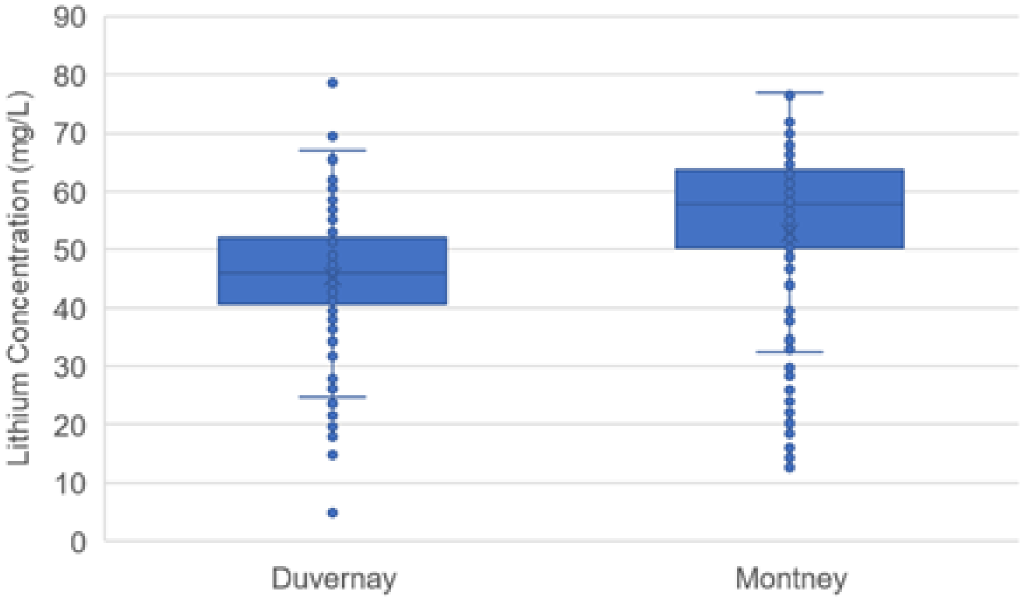

Figure 21. Formation specific lithium concentrations. Average of 45.1 mg/L for Duvernay FPW in Fox Creek, Alberta (left); and 57.7 mg/L for Montney FPW from Dawson Creek, northeast B.C. (right). Circular markers indicate the individual sample data points, while the box and whiskers represent the statistical quartiles of the data set.

4.1.5. Temporal Variation

Given the variability of the lithium concentrations within the provided FPW data, a temporal analysis of the data was used to identify trends that would be relevant from an operational perspective. A graphical summary of the lithium concentrations as a function of the age of the petroleum hydrocarbon-producing wells is presented in Figure 22.

Two notable trends are identified for the temporal variation of FPW lithium concentrations in this assessment. First, as new producing wells are brought online, the range of the lithium concentrations is wide, but on average maintains a positive slope trendline (Figure 23). This indicates that lithium concentrations of the FPW are highly variable during early production, but generally increase with time up to 180 days after initial production. The range of variability also suggests that FPW from certain wells can be more diluted as earlier flowback fluids (thus lower lithium concentration) are brought online depending on their geographic locations in the basin.

After 180 days of flowing production, as represented in Figure 24, the lithium concentration in the FPW of older wells generally demonstrates less variability. This would indicate that the lithium resource is more consistent for wells greater than 180 days as produced formation waters become dominant in the FPW as the wells age. It should be noted that of the 391 total FPW samples analyzed, 236 samples were collected at less than 180 days of production, and 152 samples were collected at greater than 180 days production.

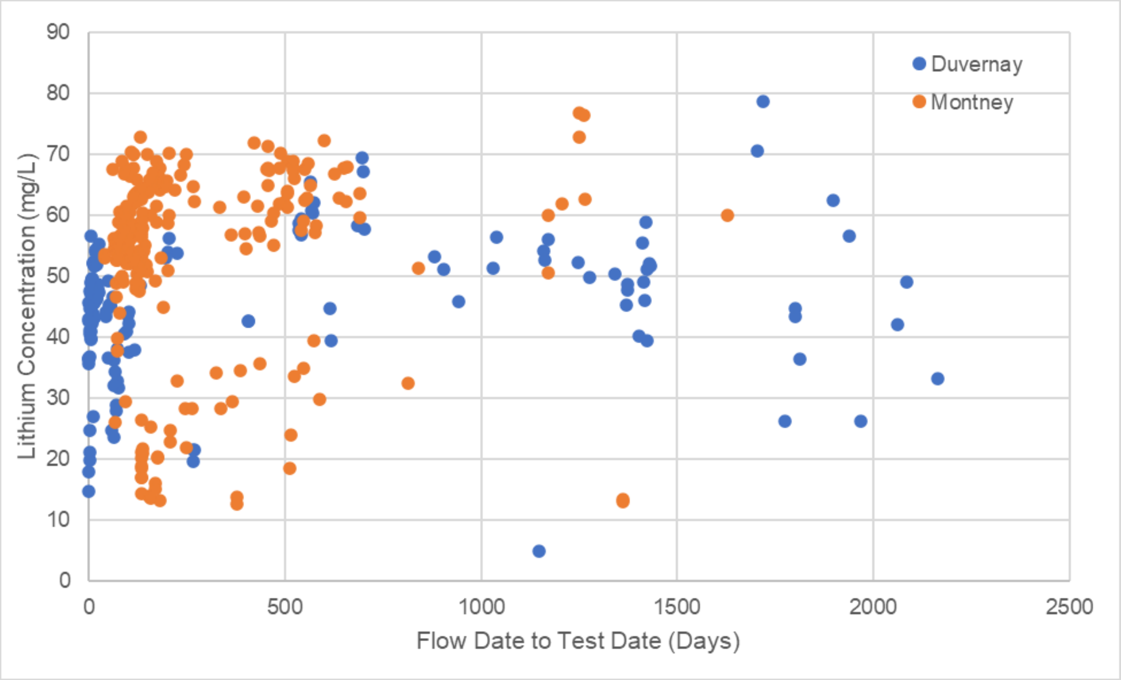

Figure 22. Lithium concentration in Duvernay and Montney FPW as a function of age of well production.

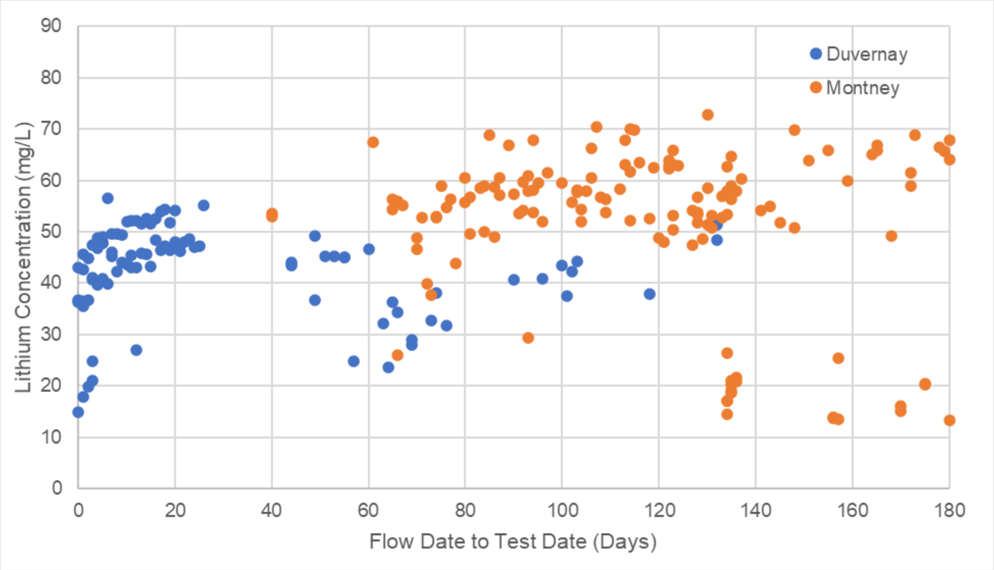

Figure 23. Lithium concentration in Duvernay and Montney FPW as a function of age of well production less than 180 days.

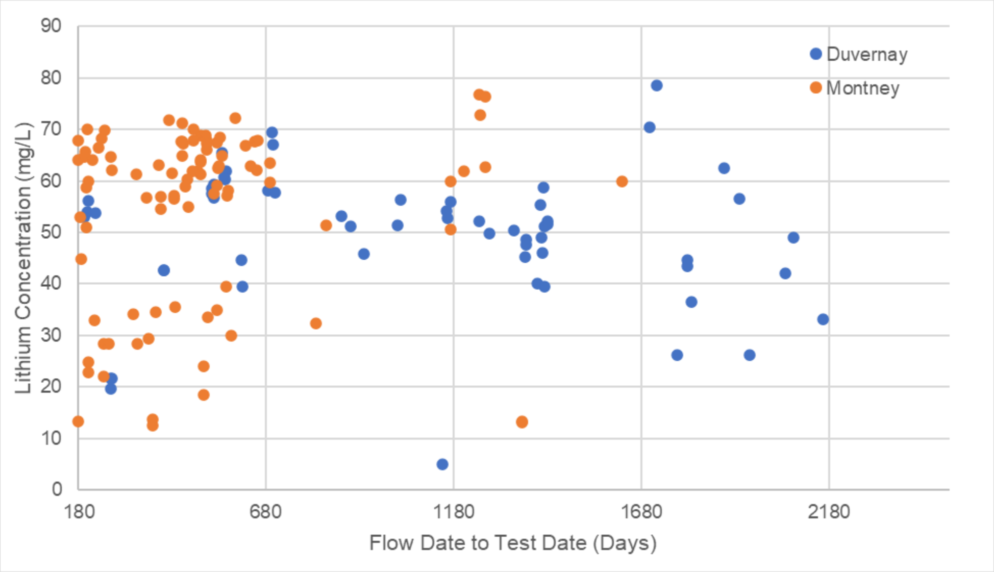

Figure 24. Lithium concentration in Duvernay and Montney FPW as a function of age of well production greater than 180 days.

It is theorized that the relationship between the lithium concentration within the FPW fluid and the age of the hydrocarbon-producing well are related to the distinction between early flowback water and later produced water. In the short term, as the age of the producing well increases, the ratio of the fluid as formation water increases, and thus the source of lithium material increases, subsequently increasing the lithium concentration in the fluid over time.

4.1.6. FPW Volume Production

The FPW fluid volume data of the select Duvernay centralized production facility is used to help determine the lithium resource potential. Per typical well production, there are rapid increases in FPW production as new production wells are brought online, followed by a more gradual decrease of produced volume over time. This is related to the distinction between high volume early flowback fluids, and low volume produced formation fluids of the well.

A summary of the daily disposal injection rate of FPW at the centralized production facility is presented in Figure 25. This disposed FPW volume would be considered the co-produced fluid that could be relied upon for potential lithium extraction activities. When considering the capital infrastructure of the lithium extraction process, a more average and sustained volume of FPW flow would yield a higher capacity utilization, and therefore more efficient capital cost utilization, compared to infrastructure sized to a maximum flow potential.

The average daily injection rate at the selected centralized facility was determined to be 1,300 m^3/day, ranging from 0 m^3/day during operational shutdowns to approximately 2,750 m^3/day at peak production.

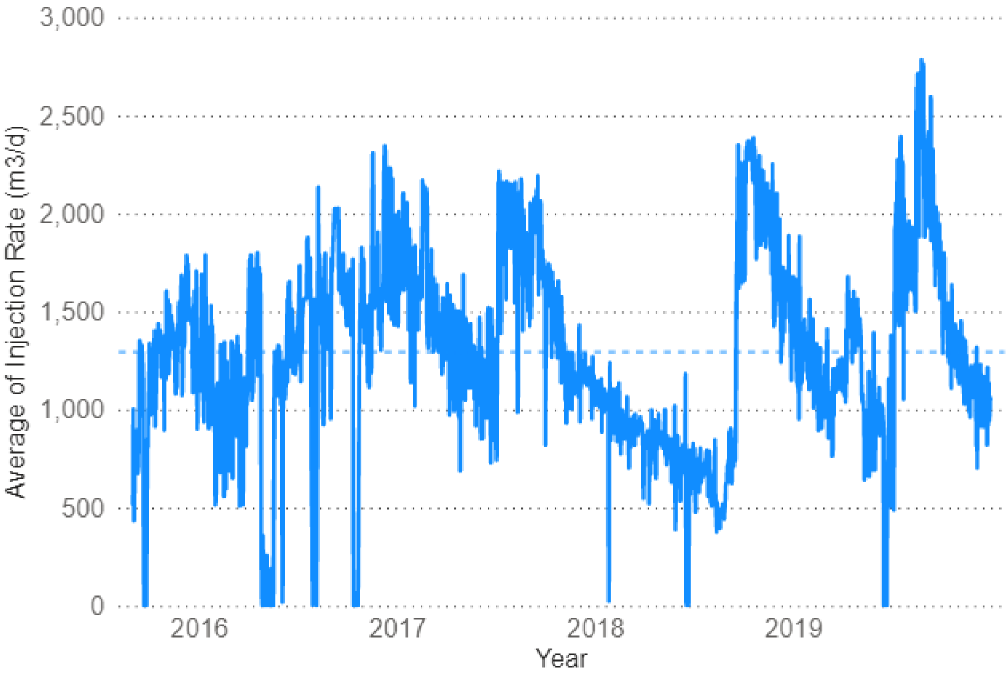

Figure 25. Historical daily FPW injection rates at the Centralized Production Facility. Average daily injection rate 1300 m^3/day.

In sizing a theoretical lithium extraction facility, the maximum brine flow through capacity was set to align with the average daily injection rate of 1,300 m^3/day, or 474,500 m^3/year. Thus, in describing the facility utilization, as a percentage of maximum, any daily FPW injection volume that exceeds 1,300 m^3/day (as 100% utilization) is considered an excess that would bypass the extraction system, and any volume less than 1,300 m^3/day is the resultant lower utilization (e.g. 858 m^3/day is equivalent to 66% facility utilization).

Based on the FPW fluid volumetric flow data at the centralized production facility, the historical total annual FPW volume available for lithium extraction (which accounts for a maximum of 1,300 m^3/day), and the resultant average annual lithium extraction capacity utilization for each year assessed is presented in Table 11. Note that the annual utilization rate is defined as the percentage of the maximum assumed lithium extraction capacity as a function of the daily FPW injection rates. Over the data period assessed (2016 through 2019 inclusive) the total average annual capacity utilization rate was determined to be 83%, ranging from 71% in 2018 and 93% in 2017. Accordingly, this utilization rate accounts for facility downtime, daily FPW disposal volumes to a maximum of 1,300 m^3/day, and any daily volume below the design capacity as described.

Table 11: Summary of annual injection volume and extraction infrastructure Utilization rate for the Duvernay centralized processing facility

Year	Total Annual FPW Volume Available (m^3/year)	Lithium Extraction Infrastructure Annual Capacity Utilization
2016	386,419	81%
2017	441,539	93%
2018	336,386	71%
2019	411,208	87%
Average	393,888	83%

Note. Capacity utilization based on average injection rate of 1300 m^3*/day.*

It is, however, assumed for this assessment that additional onsite storage at a centralized facility would be utilized to increase the facility utilization as it relates to the lithium extraction processes. The facility utilization rate for this assessment was assumed to be 90%. This is not an unrealistic utilization rate when considering the nominal efforts required to optimize the production process flow through the marginal addition of storage. However, it is an important operational consideration to address as increased downtime or decreased utilization rates would have a negative effect on the project success potential.

4.1.7. Closure – Data Analysis

The Base Case Project Scenarios were created using the FPW fluid analytical data and the features of the selected centralized hydrocarbon production facility. These inputs were also utilized in the subsequent economic assessment. A summary of the relevant information from the data analysis is presented in Table 12. Based on the average lithium feed concentration of the FPW, the assumed annual FPW volume processed, the facility utilization rate, and the lithium extraction efficiency, total annual lithium production was determined for each of the Base Case Project Scenarios. The results of this assessment are presented in Table 12.

Table 12: Summary of FPW input data for Base Case Project Scenarios

Project Scenario	FPW Feed Lithium Concentration	FPW Feed Temperature	FPW Feed pH	Lithium Recovery Rate	FPW Volume Processed (m^3/day)	Project Scenario Lithium Material Production Rate (T Li^+ / year)
Base Case (Duvernay)	45.1 mg/L	16.1°C	5.95	90%	1,300	14.73
Base Case (Montney)	57.7 mg/L	16.1°C	4.50	90%	1,300	18.72

4.2. Discounted Cash Flow Assessment

Two assessment models were completed for each Base Case project scenario (Duvernay and Montney) in the production of either of the lithium products, LHM or LC.

4.2.1. Cost Model

The results of the CAPEX and OPEX cost model developments discussed in Sections 3.2.3 and 3.2.4 and the resultant CIRs based on annual production metrics are presented in Table 13.

Table 13: Summary of revised cost models for Project Scenario analyses

	Duvernay Project Scenario #1 ($LiOH \cdot H_2O$)	**Duvernay Project Scenario #2 (Li_2CO_3)**	**Montney Project Scenario #1 ($LiOH \cdot H_2O$)**	**Montney Project Scenario #2 (Li_2CO_3)**
CAPEX				
Project Scenario Total Capital Costs ($USD)	$6,468,000	$8,182,000	$6,147,000	$7,609,000
Annual Lithium Chemical Production Rate (tonne / year)	105.4	92.5	134.0	117.6
CAPEX Intensity Ratio ($USD / tonne product per annum)—CIR	$61,366	$88,454	$45,873	$64,702
OPEX				
Total OPEX Unit Rate ($USD / tonne produced)	$4,695	$4,950	$4,230	$4,650

As expected, and as discussed in Section 3.2.2 and presented in Table 7, the CIRs of the Project Scenarios are higher than those of the respective Reference Scenarios. The CIRs developed for the production of LHM from FPW are between 1.6-2.0 times higher than Reference Scenario #1, whereas the CIRs developed for the production of LC from FPW are between 3.4-4.2 times higher than Reference Scenario #2. These CIR differentials are in part representative of the differences between the Reference Scenario and Project Scenario input (feed) lithium concentrations and project scales (e.g. annual production).

4.2.2. DCF Analysis Results

The results of the Base Case DCF outputs for all project scenarios are summarized in Table 14 with Discounted Supply Costs and IRR presented in Figure 26. The results of the assessment indicate that the production of LHM, for both the Duvernay and Montney project scenarios, yield improved investment returns than the comparable LC project scenarios. Beyond the differences in CAPEX and OPEX costs in producing LHM and LC for each project scenario, two other external revenue-based factors which contribute to project value are worth noting. First is the notable commodity pricing difference between the two products as discussed in Section 3.3. The second feature relates to the physical properties of LHM versus LC materials. Referring to Table 2, for every unit of lithium (as Li^+) available, 6.06 units of LHM can be produced, comparatively only 5.32 units of LC can be produced. Thus, approximately 14% more units of LHM are produced for every unit of Li^+ input available as compared to producing a LC material.

Table 14: Summary of Project Scenario DCF results

	Units	**Duvernay Project Scenario #1 (LHM)**	**Duvernay Project Scenario #2 (LC)**	**Montney Project Scenario #1 (LHM)**	**Montney Project Scenario #2 (LC)**
Battery Chemical Production	Tonnes/year	105.4	92.5	134.0	117.6
Before Tax Supply Cost (Discounted)	$USD/Tonne	$6,032	$7,096	$4,898	$5,758
Taxes and Royalties (Discounted)	$USD/Tonne	$4,243	$2,742	$5,182	$3,448
After-Tax & Royalty Supply Cost (Discounted)	$USD/Tonne	$10,275	$9,838	$10,080	$9,206
Year 1 Total Operating Costs	$USD Million	$0.495	$0.521	$0.566	$0.625
Year 1 Gross Revenue	$USD Million	$3.163	$2.313	$4.019	$2.939
Internal Rate of Return (IRR)	%	38.4%	$22.7%	48.1%	29.2%
Profitability Index	-	2.95	1.76	3.71	2.46
Payback Period (Discounted)	Years	2.32	5.63	1.51	3.74
Net Present Value (NPV)	$USD Million	$12.611	$6.256	$16.657	$9.577

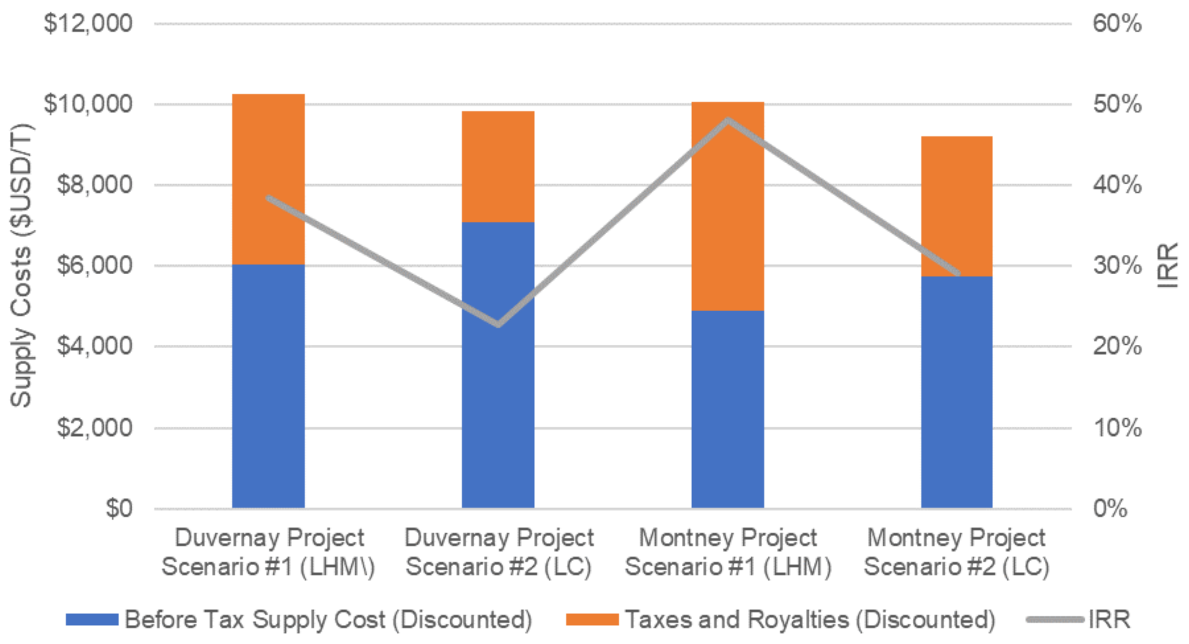

Figure 26. Project Scenario supply cost and IRR comparison.

The combination of cost and revenue factors of the product types result in a significant difference in comparable project revenues. In both scenarios where LC is the primary product, the IRRs are less than the comparable scenarios where LHM is produced and are only marginally above the minimum investment threshold of 22% as discussed in Section 3.5.

When considering jurisdictional differences (e.g. Duvernay versus Montney) for a common material produced, the results indicate that developments within the Montney yield a higher economic return. The difference in project value can be mainly attributed to two factors. First, the theoretical Montney project yields 27% more material production, simply due to a higher input feedstock concentration. Second, the lower provincial cost modifier and the lower cost electricity rate identified in British Columbia influence the supply costs of the project and thus increase project value in British

Columbia. Arguably, more competitive electricity rates could be negotiated within Alberta, but this consideration is outside of scope for this assessment.

4.2.2.1. Sensitivity Analysis

The results of the sensitivity analysis which assesses the effects of CAPEX, OPEX, and Feedstock Concentration on the After Tax & Royalty Supply Cost (Discounted) and IRR are illustrated in Figure 27 and Figure 28.

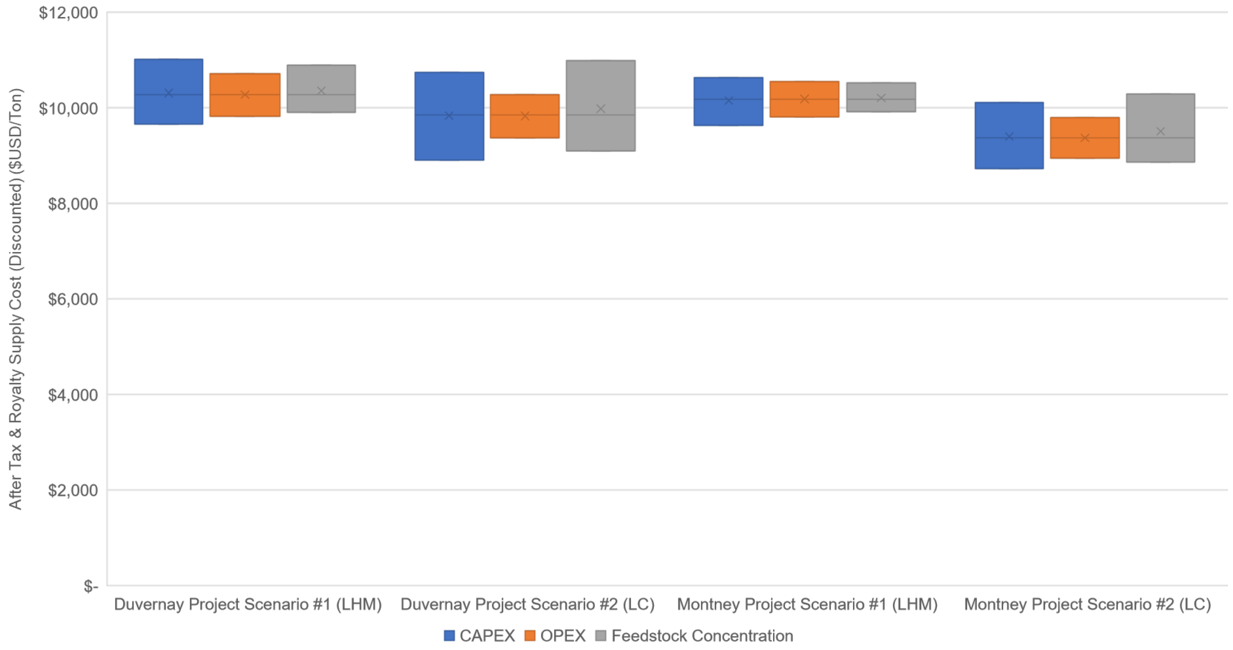

Figure 27. Effects of CAPEX, OPEX and feedstock concentration on After Tax & Royalty Supply Cost (Discounted).

The After Tax & Royalty Supply Cost (Discounted) values for each Project Scenario were shown to be most sensitive to both CAPEX and feedstock concentrations, and to a lesser extent, variations in the OPEX costs. This can be fundamentally attributed to the discounted cash flow analysis, in that the time value of money is considered in project investments. Therefore, the sensitivity changes to the initial capital investments for these projects outweigh the sensitivity changes to the annual operating costs that are incurred as materials are produced.

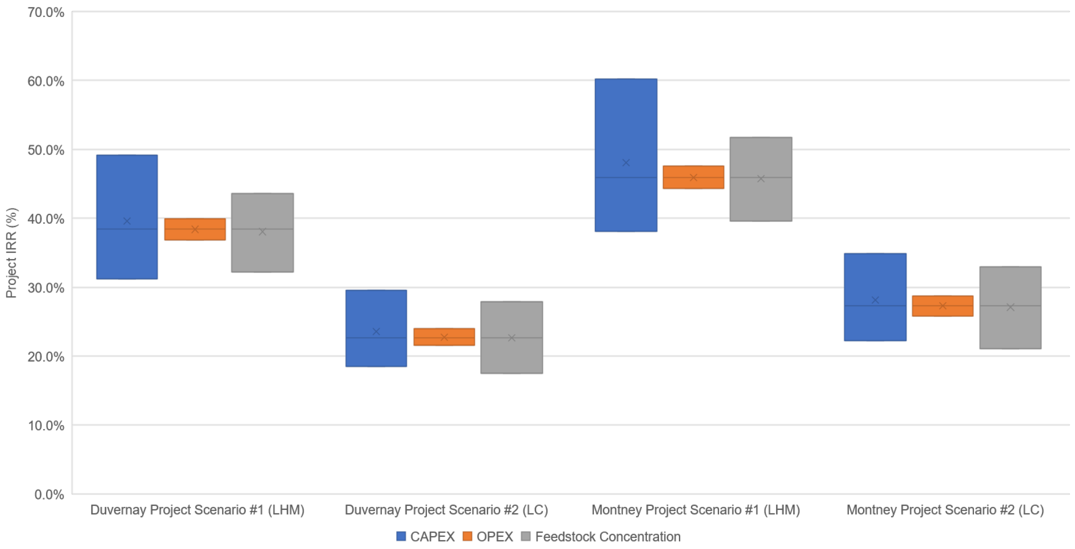

Figure 28. Effects of CAPEX, OPEX and feedstock concentration on project IRR.

From this, the IRR for each project scenario is shown to be very sensitive to variations in CAPEX costs, and to a lesser extent, lithium feedstock concentrations. Whereas variations in the OPEX costs have minimal effects on the project IRRs. Once again, the high sensitivity of CAPEX is attributed to the discounted cash flow analysis, in that the time value of money is considered in project investments. The moderate to high sensitivity of feedstock concentration on the project IRR is two-fold. First, one must consider the operating efforts to prepare a volume unit of FPW fluid for lithium extraction, and second, the quantity of lithium that is then produced as a result of those efforts. Inherently, with a decreased feedstock concentration, more brine fluid is required to produce a unit mass of lithium chemical (LHM and LC), and when FPW volume processing rates (e.g., daily) are held constant, less product is produced over the life of the project. Where possible, one could consider increasing fluid processing rates to increase production quantities and increase revenues to counter the time value effects of the initial CAPEX, but the inherent operating costs would remain high.

In the case of both Project Scenarios (Duvernay and Montney) where LC is produced, the effects of increasing CAPEX by 25% from the Base Case, and the effects of decreasing feedstock concentrations by 25% from Base Case were found to reduce the project IRRs below the acceptable IRR threshold of 22%, as discussed in Section 3.5.

4.2.3. Analysis Closure

Analysis of both Duvernay-based and Montney-based FPW fluids indicate elevated lithium concentrations and the potential for profitable investments in the development of these projects. The analysis indicated that the production of lithium hydroxide monohydrate (LHM) was a preferred product material given the increased value of the commodity on a per mass basis, and the increased quantity of end product material per unit of raw lithium.

Although feedstock concentrations are out of the control of the oil and gas producer and not the priority focus of their development, the chemical analysis of FPW fluids did indicate a higher lithium enrichment of fluids from the northeast B.C. Montney than those of the Alberta Duvernay. Total CAPEX project costs are marginally lower in B.C., primarily due to the applied jurisdictional multiplier. Further, higher Li^+ concentrations result in notable lower OPEX costs per unit of production. The combination of lower up front CAPEX costs, and lower ongoing OPEX costs result in lower before tax supply costs for the B.C. Montney project scenarios, and thus a comparatively better project investment when considering same battery chemical production types.

Given that the taxes and royalties paid on mineral projects of this nature are linked to the profitability of the development, the B.C. Montney project scenarios pay comparatively higher taxes and royalties per unit of production than the Alberta Duvernay project scenarios when considering same battery chemical production types. Overall though, the total after-tax & royalty supply costs of the B.C. Montney project scenarios remain lower than those of the Alberta Duvernay project scenarios.

While both the CAPEX and OPEX cost models developed in this analysis are subject to interpretation and recent global events such as COVID-19 and Russian-Ukrainian War have affected the global industrial supply chain, the sensitivity analysis conducted indicates strong investment potential for the B.C. Montney project scenarios. Further, the conservative pricing applied to the battery chemical revenues suggest there is further potential upside to a development as domestic demand for batteries increases.

In future analysis, however, it is important to consider the global economy and industrial supply chain as a critical external factor which is currently experiencing high rates of inflation, and increased material and labor costs. Also, critical when comparing potential development opportunities are the industrial electricity rates that would affect the ongoing operating costs of the project. A low-cost, independent power purchase agreement in Alberta would be a key consideration, while leveraging the existing low cost electricity in B.C. is critical, particularly when accounting for the quantity of electricity required to produce the various lithium battery chemical materials.

In summary, the lower total after-tax & royalty supply costs, and the larger quantities of material production for both B.C. Montney based project scenarios are shown to have greater investment potential than the Alberta Duvernay project scenarios.

Chapter 5. Discussion

As society transitions towards a low-carbon economy, increased utilization of energy storage systems and EVs is forecast to increase the demand for rechargeable batteries including lithium-ion batteries. This increased demand must be matched by a supply increase to keep end-product consumer prices at a level that does not inhibit further implementation. Beyond the existing raw lithium production from hard rock mineral deposits in Australia, and continental brine deposits in South America and China, alternative sources are being explored.

Typically viewed as a waste-product of the unconventional oil and gas industry, the flowback and produced water that emerges alongside ongoing resource production is generally considered a waste product. Nevertheless, recent data collected by the Geological Survey of Canada in Calgary from samples of FPW collected and analyzed from select producers operating within the Duvernay Shale gas development region of Alberta and the Montney development region in British Columbia suggest the presence of a significant lithium resource. This discovery has the potential to not only offer added investment value from the current waste stream, but also to support the ongoing energy transition.

Various DLE technologies have been explored as an alternative to the more traditional solar evaporation and precipitation method used to produce lithium from brine. Although the technologies associated with DLE have not been commercialized for use within existing lithium-from-brine-producing operations, ion exchange processes using lithium ion sieves have shown academic and lab-scale success. Aside from the DLE processes, the remaining processes required to purify, concentrate, and produce the battery grade lithium products from brine fluids are commercially practiced within other brine-producing regions, and could easily be commissioned in new lithium-producing operations (Worley, 2019).

Operationally, consideration needs to be given to several specific FPW characteristics that affect the lithium extraction efficiencies and the rate of extraction from the feed source:

(1) Given that the proposed ion-exchange process is pH-dependent, brine pre-treatment is required to ensure the brine feedstock is processed to within the optimum near-neutral pH range of 7-8;

(2) Fluid temperatures, which affect the rate of lithium extraction in the ion-exchange process, are on average significantly lower at the centralized hydrocarbon processing facilities than the optimal process range of 60-70°C. Thus, additional process optimizations (e.g. waste heat capture) should be considered to increase the feedstock FPW fluid temperatures, thus increasing the rate of lithium extraction, and minimizing the FPW residence time in the system and the associated infrastructure requirements;

(3) Though not explicitly addressed in this study (as the provided FPW analysis data did not contain the specific parameters), the presence of both total suspended solids and dissolved organic carbon are noted to negatively affect the lithium extraction efficiencies of the system. FPW pre-treatment efforts, focusing on the reduction of these parameters, should be assessed in greater detail to determine

the effect on lithium extraction efficiencies and resulting capital and operating costs;

(4) Temporal patterns in lithium concentration were identified from the data analysis that suggested there is a relationship between the lithium concentration within the FPW and the age of the corresponding hydrocarbon-producing well. Operational considerations should be given to the nature of the FPW production to avoid or manage lithium extraction efforts during the early stages of new well production.

In establishing the capital and operating cost models associated with the project scenarios presented here, two large-scale proposed lithium-from-brine operation references, one for producing $LiOH \cdot H_2O$ (LHM) and the other for producing Li_2CO_3 (LC) were utilized as a baseline cost development. After evaluating the selected reference cases, it was determined that certain costs needed to be removed, adjusted, or added based on the unique characteristics of the project scenarios and the parameters identified for the FPW. In order to substantiate the methodology used to determine the capital and operating costs, it was assumed that the overall magnitude of several developments in either of the producing regions was similar to that of the reference cases.

Brine-based lithium production from both Duvernay and Montney FPW fluids shows great potential for development with current high market prices, advancement of DLE technology, and increased domestic demand due to international and domestic battery production. Market entry timing will prove to be critical for any potential development given the strength of the current market conditions and the potential for other international developments that could fulfill the short and mid-term demand.

Chapter 6. Conclusions

This study shows that co-produced flowback and produced Water (FPW) from existing unconventional oil and natural gas production is potentially a viable source of raw lithium material for the production of lithium battery end-products.

Duvernay-based FPW fluids were found, on average, to have a lithium concentration of 45.1 mg/L. If processed at a select Alberta-based Duvernay facility, the lithium contained in this fluid could produce either 92.5 tonnes of lithium carbonate or 105.4 tonnes of lithium hydroxide monohydrate per annum. A discounted cash flow analysis determined after tax and royalty internal rate of return (IRR) of 23% in the production of lithium carbonate, and 38% in the production of lithium hydroxide monohydrate.

Comparatively, northeast B.C.-based Montney FPW fluids were found to have on average a lithium concentration of 57.7 mg/L. If processed at a modelled centralized facility, 117.6 tonnes of lithium carbonate or 134.0 tonnes of lithium hydroxide monohydrate could be produced per annum. A discounted cash flow analysis determined after tax and royalty IRR of 29% in the production of lithium carbonate and 48% in the production of lithium hydroxide monohydrate within the Montney development area.

Technical and operational challenges that differ from traditional lithium-from-brine production operations were identified. Data analysis indicates there is a relationship between the lithium concentration within the FPW and the age of the corresponding hydrocarbon-producing well. Beyond lithium feedstock concentrations, total suspended solids, dissolved organic carbon, fluid temperatures and fluid pH are all relevant considerations when assessing the efficacy of ion-exchange based lithium extraction from FPW fluids. Managing or addressing these fluid contaminants and their properties will have a direct effect on the overall economic viability of the development. Significant capital savings were also achieved through the concept of co-production, due to the inherent existing infrastructure utilized to produce, transport, collect and dispose of the FPW fluids.

The results of our study indicate that oil and gas producers operating in specific areas of Alberta and British Columbia contain elevated concentrations of lithium in the formation water, and from this have the potential to support the energy transition in a manner that can benefit their existing business models.

6.1. Limitations

While this research has showcased the potential feasibility of extracting lithium from FPW in existing oil and gas developments, there are certain limitations to this study. The most notable limitation is that the size of the developments analyzed in this study is considerably smaller than that of the lithium-from-brine operations in the Reference Scenario. Many brine-based operations have, or propose to have, annualized production that exceeds 10,000 tonnes LCE per year (Roskill Information Services Ltd., 2021b). The cost models developed for this study were based on the assumption of collaborative production within a regional hydrocarbon development area, resulting in a considerably higher lithium output than what was outlined in the individual Project Scenarios.

With an understanding of the current operations at the individual centralized facilities, the lithium extraction systems can be appropriately sized to align with the characteristics of the production facility. However, the purification, concentration, crystallization and end-material production facilities require a more constant stream of feedstock concentrates than what a single extraction project can provide. To completely evaluate the viability of a lithium industry, beyond merely extracting lithium from FPW, it is imperative to examine potential collaboration among regional operator groups and downstream off-takers to justify investment in a lithium battery chemical product refining and manufacturing facility.

Additionally, it is essential to consider the remainder of the lithium battery supply chain. A lithium-ion battery is comprised of numerous other materials and components, beyond the lithium carbonate or lithium hydroxide monohydrate materials. Given the establishment of the Critical Minerals and Metals action plan in North America, government agencies must support the development of the entire supply chain by linking individual component manufacturers and advancing domestic production.

6.2. Future Research

The following recommendations and future research opportunities are intended to guide existing oil and gas producers and collaborative project developers in in optimizing the potential and financial feasibility of the alternative lithium resource.

6.2.1. Strategic Field Sampling Program

The results of the 106 Duvernay and 200 Montney FPW samples analyzed proved valuable for this assessment. Nevertheless, a well-planned field sampling initiative encompassing all varieties of oilfield brines is imperative to validate the alternative lithium resource (e.g. petro-lithium) as a viable alternative for developers or investors.

As the unconventional shale and tight gas developments in Western Canada are anticipated to play a significant role during the transition to a low- or zero-carbon economy, developing an in-depth understanding of the lithium resource concentration within FPW in the short and medium terms as new production wells are established would be crucial for a project developer. A more thorough understanding of these temporal variations would aid in process optimization and operational enhancements to optimize extraction efficiencies and ensure economic viability.

Further, a comprehensive and strategic FPW sampling initiative concentrated on multiple targeted centralized production and processing facilities would once more furnish a greater understanding of the available resource potential. In this strategic sampling program, the analysis of FPW should encompass the contaminating substances and parameters (such as TSS, dissolved organic carbon, temperature, and pH) that were found to influence extraction efficiencies or the quality of the final lithium product.

6.2.2. Field Pilot Programs

As the DLE systems identified in this study are most closely aligned with Technology Readiness Level 7, field pilot studies are necessary to authenticate and enhance the technology. As the incremental infrastructure required to connect the extraction systems to existing FPW production is limited, a collaborative approach should be taken to capitalize in this and minimize the capital costs associated with field deployment and testing. In this regard, government-supported programs that offer grant opportunities or access to low-interest loans for early adopters and field pilot programs could be useful in reducing front-end capital infrastructure costs and supporting the advancement of this early-stage technology.

6.2.3. Environment and Life Cycle Assessments

Although this study briefly addressed the environmental impacts associated with lithium production from mineral and brine sources, it is imperative to conduct further research to quantify the life cycle impacts of DLE processes. Regions or jurisdictions that have access to low-carbon or renewable energy sources could potentially support the development of alternative lithium resources due to the significant energy requirements needed for the transportation, extraction, purification, and refining of raw lithium into a usable end-product. Consideration of the greenhouse gas emissions and freshwater usage associated with lithium production could be relevant if environmental, social and governance metrics, carbon border adjustments, and carbon taxes are applied to lithium-ion batteries within electric vehicles and energy storage systems.

6.2.4. Continued Exploration of Lithium in Other Hydrocarbon-Producing Regions

This study has primarily examined the potential for lithium production in the Duvernay shale gas developments of Alberta and the Montney tight reservoir operations in British Columbia. However, there may be additional opportunities for lithium resources in other producing regions. Future research that helps identify other areas within the Western Canadian Sedimentary Basin that exhibit elevated concentrations of lithium minerals, could support the potential of a domestic lithium industry in Western Canada.

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Appendix A: Scenario Analysis and Discounted Cash Flow Analysis

Step 1 – Relevant Chemical and Physical Properties of FPW

1. Determine average FPW fluid pH, dissolved parameters, dissolved lithium (as mg/L Li^+), and average fluid temperatures.
2. Consider temporal variations in assessment.

Step 2 – Volume Characteristics of Development(s)

1. Determine system FPW volume capacity (FPW m^3/day and m^3/year).
    a. Volume of FPW that is managed by the system daily and annually.
    b. Information provided by project partner.

Step 3 – Mass Characteristics of Development(s)

1. Determine system Lithium mass capacity
    a. Mass of lithium (as Li^+) that flows through system on a daily and annual basis.
    b. Inputs - Step 1 (concentration) and Step 2 (volume capacity of system).
    c. Output – Li^+ tonne/day and tonne/year.
    d. Lithium extraction system efficiency at 85% of input concentrations.
    e. Conversion factors to battery chemicals based on Table 2.

Step 4 – Capital and Operating Unit Costs of Development(s)

- Create comparative cost models using outputs of Step 1, Step 2 and Step 3 (lithium concentration, volume of FPW, and mass of lithium), and information from representative lithium project reference scenarios.
- Apply jurisdictional multipliers to capital costs based on development location.

Alberta	**British Columbia**
1.0	0.93

- Determine capital intensity ratios for comparison to project reference scenarios.

Step 5 – Scenario Discounted Cash Flow Analysis

1. Determine Annual Operating Costs
    - Operating Costs ($) = Annual Production (tonnes) x Operating Unit Costs ($/tonnes)
2. Determine Revenues
    - Revenue ($) = Annual Production (tonne) x Unit Pricing ($/tonne)
    - Battery chemical pricing is applied based on the year of production and pricing increase per below and as described in Section 3.3.

Year of Project	Lithium Carbonate (Li_2CO_3)		Lithium Hydroxide Monohydrate ($LiOH\cdot H_20$)	
	Pricing ($USD/tonne)	Year-over-Year Increase (%)	Pricing ($USD/tonne)	Year-over-Year Increase (%)
2022	$ 25,000	-	30,000	
2023	$ 25,000	0%	30,000	0%
2024	$ 27,000	8%	32,000	7%
2025	$ 29,000	7%	34,000	6%
2026	$ 31,000	7%	36,000	6%
2027	$ 33,000	6%	38,000	6%
2028	$ 35,000	6%	40,000	5%
2029	$ 35,700	2%	40,800	2%
2030	$ 36,414	2%	41,616	2%
2031	$ 37,142	2%	42,448	2%
2032	$ 37,885	2%	43,297	2%
2033	$ 38,643	2%	44,163	2%
2034	$ 39,416	2%	45,046	2%
2035	$ 40,204	2%	45,947	2%
2036	$ 41,008	2%	46,866	2%
2037	$ 41,828	2%	47,804	2%
2038	$ 42,665	2%	48,760	2%
2039	$ 43,518	2%	49,735	2%
2040	$ 44,388	2%	50,730	2%
2041	$ 45,276	2%	51,744	2%
2042	$ 46,182	2%	52,779	2%

3. Determine Annual Net Income at time period n
   - Annual Net Income ($) = Revenue ($) – Operating Costs ($)
4. Determine Accumulated Net Cashflow Before Royalties to time period n
   - Accumulated Net Cashflow Before Royalties$_n$ ($) = $\sum_{n=0}^{n}$ Accumulated Net Income ($) – Capital Costs($)
5. Determine Annual Royalties Paid at time period n
   - Annual Royalties Paid$_n$ ($) = Annual Net Cashflow Before Royalties$_n$ * Royalty Rate

Royalty Stage	Alberta	British Columbia
Pre-Capital Payout	1%	2%
Post-Capital Payout	12%	13%

6. Determine Pre-Tax Operating Cash Flow at time period n
   - Pre-Tax Operating Cash Flow$_n$ = Net Income$_n$ – Royalties$_n$

7. Determine Capital Cost Allowance per operating year at time period n
    - Canadian accelerated capital costs allowance provisions under Class 43.1 and 43.2

Year	First-year enhanced allowance
2023	100%
2024	75%
2025	75%
2026	55%
2027	55%

8. Determine Taxable Income at time period n
    - Taxable Income$_n$ ($) = Pre-Tax Operating Cashflow$_n$ ($) – Capital Cost Allowance$_n$ ($)
9. Determine Taxes Paid at time period n
    - Taxes$_n$ = Taxable Income$_n$ * Effective Tax Rate
    - Add table

Jurisdiction	Effective Tax Rate (%)
Alberta	23
British Columbia	26

10. Determine After Tax Operating Cashflow
    - After Tax Operating Cashflow ($) = Pre-Tax Operating Cashflow ($) – Taxes Paid ($)
11. Determine After-Tax & Royalty Supply Cost (CF$_n$) at time period n

$$CFn = \frac{\sum(Capital\ Cost + Operating\ Costs + Taxes + Royalties)_n}{Total\ Lithium\ Production\ (tonne\ LCE)_n}$$

12. Determine Present Value (PV) of After Tax Operating Cashflow (CF$_n$)

$$PV_n = \frac{CF_n}{(1+DR)^n}$$

PV$_n$ = Present Value of After Tax Operating Cashflow at time period n
CF$_n$ = After Tax Operating Cashflow at time period n
DR = Discount Rate
n = Time period of the cash flow from 0 to nth period

13. Determine Project Net Present Value (NPV) of scenario cashflows (CF$_n$)

$$NPV = \sum_{n=0}^{n} \frac{CF_n}{(1+DR)^n} = \sum\nolimits_{n=0}^{n} PV_n$$

14. Determine Discounted Payback Period
    - Number of time periods where initial capital costs equal sum of Present Value After Tax Operating Cashflow (PVn)

$$Discounted\ Payback\ Period = \frac{Capital\ Cost}{(\sum_{n=0}^{n} PV_n)}$$

15. Determine Internal Rate of Return

$$NPV = 0 = \sum_{n=0}^{n} \frac{CF_n}{(1+IRR)^n}$$

NPV = Net Present Value of After Tax Operating Cashflow = 0
CF$_n$ = After Tax Operating Cashflow at time n
IRR = Internal Rate of Return ("Discount Rate") to return NPV = 0
n = Time period of the cash flow from 0 to nth period

16. Determine Profitability Index

$$Profitability\ Index = \frac{NPV}{Capital\ Cost}$$

17. Sensitivity Analysis
    - Run each scenario analysis and discounted cash flow analysis with variable modifications:

Variable	**Sensitivity Range**
CAPEX	-25% to +25%
OPEX	-25% to +25%
Lithium concentration in brines	-25% to +25%